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RESEARCH MEMORANDUM

ANALYTICAL STUDY OF THE COMPARATIVE PITCH-UP BEHAVIOR OF SEVERAL AIRPLANES AND CORRELATION WITH PILOT OPINION

By Melvin Sadoff, John D. Stewart, and George E. Cooper

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Moffett Field, Calif.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The method of NACA RM A55D06 was used in an analytical study of the comparative pitch-up behavior of six jet-powered swept-wing airplanes. The effects of several important variables, including recovery control rate, entry rate, and altitude are assessed.

Also presented is a correlation with pilot opinion of the computed pitch-up characteristics for the six airplanes which had pitch-up behaviors ranging from mild to severe.

INTRODUCTION

One of the important problems encountered in the design of swept-wing airplanes is that of insuring that the pitching moments do not exhibit destabilizing tendencies with angle of attack throughout the transonic Mach number range. Since available data for most current swept-wing airplanes do exhibit destabilizing tendencies in varying degrees, it is evident that this problem has not been satisfactorily resolved. Pitch-up tendency has increased the possibility of inadvertently exceeding the design wing and tail loads. It also has either limited controlled maneuvering to load factors below the pitch-up boundary or resulted in a significant reduction in controllability. It appears desirable, therefore, to have some method for predicting the airplane motions and the associated pilot opinion from wind-tunnel data.

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In one of the first analytical studies relating to the pitch-up problem (ref.1), a method was derived for studying some of the factors affecting pitch-up behavior, such as the shape of the pitching-moment curve, control motion, dynamic pressure, airplane inertia in pitch, and varying aerodynamic characteristics with Mach number. However, since the control inputs used in this previous work did not include the effect of airplane motion feedback on pilot response, the method was not considered generally applicable to the present study. Therefore, a suitable evaluation maneuver was developed using a ground pitch-up simulator with experienced test pilots as operators. Detailed results of this study are reported in reference 2.

As an extension of the work presented in reference 2, the method was applied to six swept-wing airplanes for which pilot opinion was well documented. The analytical results obtained are used herein to illustrate how wind-tunnel data may be used to predict the pitching motions and the comparative pitch-up behavior of new airplane designs or to assess the effects of modifications on existing airplanes. The results are also correlated with pilot opinion in an attempt to determine the significant factors that influence a pilot's over-all opinion of pitch-up.

DESCRIPTION OF AIRPLANES

Six jet-powered swept-wing airplanes, with sweep angles ranging from 35° to 45°, were included in this study. Five of the airplanes studied were fighter types and one was a bomber. Two-view drawings of these airplanes and their pertinent physical characteristics are presented in figure 1 and table 1, respectively. One airplane, the F-86A, was tested both in the production configuration and with a wing modification comprised of blunt trailing-edge ailerons which is described in reference 3.

METHOD

Evaluation Maneuver

The evaluation maneuver used to obtain the basic time history data of this report is the same as that used in reference 2. In this reference a method was introduced for analytically studying the pitch-up behavior of an airplane by computing certain critical response quantities for an assumed standard control movement by the pilot. This prescribed evaluation maneuver, or pilot behavior, was based on a study of pilot reaction times and pitching-acceleration threshold characteristics determined from tests in a modified Link trainer. In this maneuver the pilot is assumed first to apply nose-up longitudinal control at one of several constant rates, corresponding to entry rates into the pitch-up region, of 0.2, 0.5, and 1.0g per second. The onset of pitch-up is assumed to be detected by the pilot when the pitching-acceleration response exceeds the pilot's threshold level[1] of 0.15 radian per second per second above the steady-state value. During the pilot's response time of 0.4 second he continues to apply nose-up control at the initial rate. He then applies corrective control at one of several constant rates from 0° per second to the maximum assumed for each case. At the higher recovery control rates, it was assumed the stick was moved to the forward stop, then held fixed. A representative time history of this evaluation maneuver, as applied to one of the airplanes studied, is shown in figure 2.

It was found necessary to modify the evaluation maneuver slightly for configurations with a pitch-up so mild the pitching acceleration did not attain the threshold value. For the B-47 airplane it was arbitrarily assumed that corrective control was applied at the time the peak pitching acceleration was reached. The threshold value of pitching acceleration, therefore, was that existing 0.4 second prior to the application of corrective control.

The control inputs used in this study were established for two altitudes for each airplane considered. The upper altitude, 35,000 feet, was selected to correspond to that at which most of the stability tests were performed on these airplanes in flight and where most of the documented pilot opinion was obtained. The lower altitude chosen was that at which the pitch-up region (defined herein as the angle of attack at which the local C_{m_α} is zero or a minimum) was just penetrated in a 6g ($\Delta n = 5g$) maneuver for the fighter airplanes. For the B-47 bomber, a lower entry value of 3g ($\Delta n = 2g$) was chosen. For reference, the nominal design load factors are 7.33g for the fighters and 3.5g for the bomber airplane.

Since flight experience indicated that the pitch-up was generally most severe at a Mach number of about 0.90 for the transonic fighters studied, computations were made for this speed. For the bomber, speed limitations dictated a somewhat lower Mach number (0.80) for the computations.

Computation Procedure

For this study, a constant speed maneuver for a rigid airplane in quasi-steady flow is assumed. The longitudinal equations of motion for excursions from steady-state ($n = 1.0g$) flight may be then written as

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[1]It should be recognized that pitching accelerations which exceed this threshold level during the initial transient phase of the maneuver are disregarded, since the pilot would associate these values with his control input rather than pitch-up.

$$-mv(\dot{\theta}-\dot{\alpha}) = \Delta Z(\alpha)+Z_{\delta}\Delta\delta \tag{1}$$

$$I_y\ddot{\theta} = \Delta M(\alpha)+M_{\dot{\alpha}}\dot{\alpha}+M_{\dot{\theta}}\dot{\theta}+M_{\delta}\Delta\delta \tag{2}$$

A Reeves Analog Computer was used to obtain solutions to equations (1) and (2) for the longitudinal control inputs established by the method outlined in the preceding section. The nonlinear functions $\Delta Z(\alpha)$ and $\Delta M(\alpha)$ were obtained in coefficient form from figure 3. Other important dimensional and aerodynamic data are presented in tables I and II, respectively. It should be noted that the values of $M_{\dot{\alpha}}$, $M_{\dot{\theta}}$, M_{δ}, and Z_{δ} were assumed invariant over the angle-of-attack range, since data were not available to define the variations of these quantities with angle of attack.

It will be noted in figure 3 that the unmodified F-86A and the F-86F airplanes, which are almost identical dimensionally, have pitching-moment curves which differ considerably. It is believed most of this apparent discrepancy is due to differences in wing leading-edge configuration. The F-86A wing has a slatted leading edge, while the F-86F considered in the present analysis has the solid 6-3 leading-edge modification, which consists of an extension of the wing leading edge 6 inches at the root and 3 inches at the tip. Another secondary reason is that in the derivation of the pitching-moment curves for these airplanes from flight data a constant control effectiveness was assumed. Actually, the elevator effectiveness for the F-86A airplane increased at the higher angles of attack (due to a decrease in Mach number) so that the actual unstable break in the pitching-moment curve is slightly less than that shown in figure 3. The effect on the computed dynamic behavior of the F-86A in the pitch-up region is believed negligible, however.

The computed response quantities of primary interest include incremental angle of attack $\Delta\alpha$, incremental load factors Δn and $\Delta n'$, pitching acceleration $\ddot{\theta}$, and incremental maneuvering tail load ΔL_{t_M}. These symbols and others used in this report are defined in Appendix A.

RESULTS OF COMPUTATIONS

Detailed results of the computations are presented in figures 4 through 9 for the six airplanes studied which had pitch-up behaviors varying from mild to severe. These results cover the effects of several important variables including recovery control rate, entry rate, and altitude.

Effect of Recovery Control Rate

Representative time histories of pitch-up maneuvers at 35,000 feet for an entry rate of about 0.5g per second are presented in figure 4 showing the relative severity of airplane motions during pitch-up for the six airplanes considered. (The vertical lines in these figures indicate the times at which the pitching-acceleration threshold was attained.) Generally, as recovery control rate is increased, the angle-of-attack and load-factor overshoots are decreased and the peak negative pitching accelerations (or positive maneuvering tail-load increments) are increased. This is shown more clearly in figure 5 which presents the variation with recovery control rate of four important variables, $\Delta\alpha_{over}$, Δn_{over}, $\Delta n'_{over}$, and $\Delta L_{t_{\ddot{\theta}_{max}}}$. In general, a point of diminishing returns is reached, particularly for the airplanes with more powerful controls, in that further increase in recovery control rate results in relatively small decrements in load factor while the tail loads continue to increase significantly. These results may be useful in the preliminary design stage for optimizing the control-surface rate so that both the overshoots and the maneuvering tail loads are minimized. For a given airplane an increase in recovery control rate has the same effect on the overshoots and tail loads as an increase in control effectiveness. Therefore, these data are also useful for indicating whether increased control power would be useful for improving the pitch-up behavior of an airplane. For example, an increase in control effectiveness on the F-84F airplane by substituting an all-moving stabilizer for the elevator would be expected to improve the pitch-up behavior because of the much more rapid decrease in angle-of-attack and load-factor overshoots with recovery control rate. However, it should be recognized that a corresponding increase in the rate of build-up of maneuvering tail-load increment with recovery control rate would also be expected as can be seen in figure 8(b). Increasing the recovery control moment available by increasing the maximum down-elevator deflection would not reduce the overshoots on the F-84F airplane since the peak load factors are generally reached before the elevator has reached the existing limit down deflection (figs. 4(b) and 7(b)). Also, the peak tail loads would be increased since the limits imposed by the existing maximum down deflection would be removed (figs. 5(b) and 8(b)).

Effect of Entry Rate

Figure 5 also shows that for constant recovery control rates, appreciable increases in the attitude and load-factor overshoots generally occur as the magnitude of the entry rate ($\dot{n}_{entry}$) into the pitch-up region is increased from 0.2 to 1.0g per second. Relatively small effects on the maneuvering tail loads are shown.

Figure 6 presents the variation with entry rate of the peak positive pitching acceleration attained in these pitch-up maneuvers. In all cases, an increase in entry rate results in an increase in maximum pitching acceleration and, consequently, an increase in the maximum destabilizing moment ($I_y\ddot{\theta}_{max}$) acting to increase the overshoots.

Effects of Altitude

For flight conditions where the pitch-up region is entered at load factors close to the design values, both the wing and tail loads may assume critical values. For cases where the pilot does not attempt to check the pitch-up (zero or low recovery control rate), the airplane load factor may exceed the design values considerably. In cases where the pilot abruptly attempts to check the pitch-up (high recovery control rate), he may succeed in preventing critical wing loads, but the maneuvering tail loads may then exceed design levels. To illustrate this, the results of computations for altitudes where the pitch-up region is entered at about 80 percent of the design load factor, that is, absolute values of $6g(\Delta n = 5g)$ for the fighter airplanes and $3g$ (or $\Delta n = 2g$) for the bomber airplane, are presented in figures 7 to 9. These results may be compared with those in figures 4 to 6, to show the effects of a decrease in altitude,[2] or of an increase in the load-factor level at which the pitch-up region is entered. Generally, because of the effects of increased dynamic pressure, the load-factor overshoots and maneuvering tail-load increments are considerably increased. With reference to the results shown in figure 7, it may be seen that the design load factors were generally exceeded for all airplanes considered. The maximum computed absolute (Δn+1) values range from about 9 to 10g for the F-84F and F-86A airplanes to about 7g for the F-100 airplane. The maximum computed maneuvering tail-load increments at these higher dynamic pressures either approached or exceeded the design values for the F-84F and F-86A airplanes.

Effect of Wing Modification

The effects of blunt trailing-edge ailerons on the F-86A (ref.3) are shown in figures 5(a) and 8(a). The effects on the lift and pitching-moment characteristics are shown in figure 3. As shown in figures 5(a) and 8(a) the blunt-aileron modification reduced the overshoots, at the lower recovery rates, about 20 to 40 percent, while the maneuvering tail loads were reduced approximately 20 to 30 percent. Note that the

[2]It should be noted the lower altitude was not the same for all airplanes studied because of differences in both the C_L, where the local C_{m_α} is zero, and in wing loading.

comparisons are provided only for an entry rate of 0.5g per second. At the highest recovery control rates, the maneuvering tail loads were increased slightly by the wing modification.

CORRELATION WITH PILOT OPINION

In the preceding section, a detailed study of the pitch-up characteristics of six swept-wing airplanes was made to illustrate how the longitudinal dynamic behavior for airplanes with nonlinear pitching-moment characteristics may be predicted from wind-tunnel data. Fairly well-documented pilot opinion was available on these airplanes from flight experience obtained at about 35,000 feet altitude. This pilot opinion was obtained from six NACA research pilots in the form of numerical ratings for the items listed in table III based on the pitch-up rating schedule in table IV. The one pilot who had flight experience in all six airplanes was also the Ames Aeronautical Laboratory research pilot with the most flight experience with pitch-up. It was therefore decided to base the correlation solely on the numerical ratings he assigned to the six airplanes (table V). Pilot opinion provided by the other five NACA pilots is shown in table VI. In the following sections we will attempt to establish a correlation between the computed behavior of the six airplanes and the pilot opinion ratings in table V.

It was apparent from discussion with the pilot that his opinion of how much pitch-up limits or restricts maneuverability (question V of table III) represents the integration of a number of different factors, and the relative importance of these factors may vary depending on the flight environment. Following were some of the identifiable factors:

(a) Angle-of-attack or attitude overshoot

This factor would be expected to assume primary importance at the higher altitudes where the concern of the pilot is to maintain control of the airplane in order to avoid a stall or spin entry. It would be expected that this factor would be of less direct importance where limiting load factors are reached well before the airplane stalls.

(b) Airplane load-factor overshoot

This factor is of concern under any circumstances, but assumes increased importance at lower altitudes or higher dynamic pressures where the possibility of overstressing the airplane during pitch-up is present.

(c) Abruptness of pitch-up

The primary factor characterizing this aspect of the pitch-up appears to be the peak positive pitching acceleration $\ddot{\theta}_{max}$. Examination of the computed time histories (figs. 4 and 7) indicates that this factor generally occurs in the early portion of the pitch-up maneuver and is generally independent of the rate of corrective-control application.

(d) Controllability

This factor is related to pilot opinion regarding his ability to control the airplane during pitch-up.

In order to arrive at a general pitch-up criterion, it would obviously be desirable to correlate with over-all pilot opinion a single parameter, synthesized from the computed data, which completely integrates all of the above factors. Since this did not appear practicable, it was decided to determine whether a useful criterion might emerge simply from an examination of several of the above factors in turn. It will be noted in table III that pilot opinion was obtained on a number of different factors including several of those listed above. For example, the pilots have indicated that the attitude overshoot (item (a) above) is related to their ratings of item II(A) in table III. Also, the load factor overshoots are directly related to item IV of table III and, according to the pilots, the peak positive pitching acceleration is related to pilot opinion of the abruptness of pitch-up. Although the results are not shown, it should be noted that there is a significant correlation between the ratings of items II(A) and IV and the computed values, at low recovery control rates, of $\Delta\alpha_{over}$ and Δn_{over}, respectively. However, it was desired to determine the extent to which these computed factors influence over-all pilot opinion, so the following discussion is concerned mainly with correlation of the computed overshoots and controllability factors with an over-all pitch-up rating by the pilot based on item V of table III.

Overshoots

It seems reasonable to assume that the overshoot in angle of attack and airplane normal load factor are the two most important factors influencing over-all pilot opinion, since they are a direct measure of airplane behavior during pitch-up. To illustrate this, figure 10 was prepared to show a general relationship between the computed airplane angle-of-attack and normal-acceleration-factor overshoots and the pilot's general pitch-up rating, based on question V of table III. The computed data are for an altitude of 35,000 feet and for an entry rate of 0.5g per second, since these were the flight conditions at which pilot opinion was formed during research flights on these airplanes. These six airplanes fall into three groups according to actual flight experience and figure 10 indicates that the overshoots place them in roughly the same order; that is,

(a) The F-86A and F-84F airplanes which have an over-all pilot rating of unsatisfactory.

(b) The YF-86D and F-86F airplanes, which are rated as unsatisfactory but acceptable.

(c) The F-100A and B-47 airplanes, which are rated as marginally satisfactory.

It will be noted that though the attitude overshoots for the F-100 airplane lie in the unsatisfactory-but-acceptable group, the pilot rated the airplane as marginally satisfactory. Presumably this may be attributable to the lower airplane load-factor overshoots at the lower recovery control rates (fig. 10(b)).

In connection with the results in figure 10, a question arises as to whether the pilot actually forms his opinion over a limited range of recovery control rates. In an attempt to resolve this question, figure 11 was prepared to present a correlation of the computed attitude and load-factor overshoots for various stick-recovery rates[3] with over-all pilot opinion. The stick-recovery rates selected were 0° per second, 10° per second, 20° per second, and the maximum available for each airplane. Although no definite quantitative resolution of the above question results, it does appear that the pilot froms his opinion of pitch-up behavior primarily on the basis of overshoots associated with low to moderate recovery rates (0° to 20° per second) rather than those for the maximum rates he could apply.

The correlation shown in figures 10 and 11 tends to confirm the assumption that the angle-of-attack and load-factor overshoots are dominating factors influencing a pilot's over-all pitch-up rating. By comparing the critical computed overshoots with the corresponding computations shown in figure 10, a qualitative assessment may be made of the probable severity of pitch-up on a new airplane configuration prior to actual flight experience.

Controllability Factor

In the preceding section a significant correlation was established between over-all pilot opinion of pitch-up and the computed overshoots for several reference airplanes for which pilot opinion was well documented. In the present section, the controllability aspect of the pitch-up is examined for two reasons. For cases where the exact overshoots and tail loads are not required and where it is desired to examine rapidly the effects of a number of aerodynamic modifications with a minimum number of computer runs and a minimum amount of analysis, a pitch-up criterion based on controllability alone would be desirable. Also, in many cases,

[3]It was desired to compare the overshoots for fixed stick-recovery rates rather than control-surface rates, since the pilot is probably more directly influenced by the airplane's response to the former.

it will be shown that the overshoots and controllability of pitch-up may be roughly estimated from wind-tunnel data without performing the actual simulator studies.

From considerations presented in Appendix B, an attitude controllability factor was derived which may be given by the relationship

$$(\mathrm{C.F.})_{\Delta\alpha} = \frac{\text{Restoring moments}}{\text{Upsetting moments}} \approx \frac{M_{\delta_{stick}}}{I_y \ddot{\theta}_{max}}$$

To obtain a controllability factor related to the pilot's ability to control airplane load factor, the above relationship is simply multiplied by W/Z_{α}'. These factors were computed for the six reference airplanes and are plotted in figures 12 and 13 against over-all pilot opinion. The values of $\ddot{\theta}_{max}$ used were taken from computed time histories at an altitude of 35,000 feet and for an entry rate of 0.5g per second. Values of $M_{\delta_{stick}}$ were related to M_{δ} through the stick gearing G.[4] The correlation shown in figures 12 and 13 is fairly good, indicating that values of controllability factor may be related to over-all pilot opinion of pitch-up. The linear correlation shown in the semilog plot in figure 13 indicates that the pilot is more sensitive to changes in controllability factor at low values than he is to changes in high values. This is apparently traceable to the greater variation of overshoot with controllability factor at the lower values of $(\mathrm{C.F.})_{\Delta\alpha}$ and $(\mathrm{C.F.})_{\Delta n}$. (See fig. 14.)

In the early design stage where some of the detailed data necessary for a complete simulator study are lacking, or where it may be desired to examine rapidly the effects of a number of aërodynamic modifications without performing the actual simulator studies, a method is outlined in Appendix C for estimating approximate values of controllability factor and overshoot.

Additional Considerations

Effect of load-factor level.- An important reservation should be stressed in connection with the use of the correlation plots in figures 12 and 13, as well as figures 10 and 11. All flight experience from which pilot's opinion was derived was obtained at relatively high altitude where the load factors experienced during pitch-up were moderate. It would appear, in the first place, that at higher dynamic pressures, where the possibility of overstressing the airplane is present, the airplane

[4]In several cases where the gearing varied with surface deflection, the value corresponding to the surface deflection at the time recovery control was initiated was used.

load-factor overshoot will assume increased importance. Furthermore, the pitch-up should probably then be assessed more from a loads standpoint than from a pilot-opinion standpoint. This aspect of the pitch-up problem was touched upon in the first section of this report and is discussed in some detail in reference 2.

Effect of other modes of motion.- Another important consideration is that the correlation with pilot opinion presented herein is based only on the longitudinal dynamic behavior in the pitch-up region. For the six airplanes considered in the present study, this mode of motion was the predominating one for the flight conditions selected for analysis; that is, other modes of motion such as roll-off, directional divergence or spin entry were not sufficiently noticeable in the flight tests to influence pilot opinion. A quantitative assessment of these effects on pilot opinion is beyond the scope of this report. However, some information relating pilot opinion of roll-off at low speeds to variations in rolling-moment coefficient is presented in reference 4.

CONCLUDING REMARKS

From the results of an analytical study of the pitch-up behavior of six swept-wing airplanes and a correlation of these results with pilot opinion, the following concluding remarks were drawn.

1. Analytical techniques have been developed to study the factors affecting the important airplane response quantities in pitch-up maneuvers. These response quantities include:

    (a) Angle-of-attack overshoot.

    (b) Airplane load-factor overshoot.

    (c) Maneuvering tail-load increment.

2. For flight conditions where the pitch-up region is entered at relatively low load-factor levels of the order of 35 to 55 percent of the design value, a significant degree of correlation was established between the magnitude of the computed angle-of-attack and load-factor overshoots and pilot opinion for six airplanes with pitch-up behavior ranging from mild to severe.

3. For flight conditions where the pitch-up region is entered close to the design load factor, a method is described for estimating the range of airplane load factors and maneuvering tail loads likely to be experienced in pitch-up maneuvers. The method assumes a realistic evaluation maneuver which partially integrates airplane and pilot response.

4. Some of the detailed results of the present study are:

(a) Generally, the effect of increasing recovery control rate was to reduce the overshoots significantly, particularly for low to moderate rates, and to increase the maneuvering tail-load increments. At the higher recovery control rates, further increase in control rate resulted in relatively small decrements in load factor while the tail loads continued to build up appreciably.

(b) Increasing the entry rate into the pitch-up region from 0.2 to 1.0g per second resulted in an appreciable increase in the attitude and load-factor overshoots, while relatively small effects were observed on the maneuvering tail-load increments.

(c) At altitudes where the pitch-up region is entered at an absolute value of load factor about 6g, the design load factors were generally exceeded for most of the airplanes considered in this study. At low recovery control rates, the maximum absolute values ranged from about 9 to 10g for the F-84F and F-86A airplanes to about 7g for the F-100A airplane. The maximum maneuvering tail-load increments either approached or exceeded the design values for the F-84F and F-86A airplanes at the highest recovery control rates considered.

5. Pilot opinion for the six airplanes considered in this study indicated the following:

(a) None of the airplanes were rated completely satisfactory.

(b) The B-47 and F-100A airplanes, which were considered to have only a mild pitch-up tendency, had an over-all rating of marginally satisfactory.

(c) The F-86F and YF-86D airplanes, which had moderate pitch-up tendencies but powerful longitudinal controls, were rated unsatisfactory but acceptable.

(d) The F-86A and F-84F airplanes, which had severe pitch-up tendencies were rated as unsatisfactory.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Apr. 4, 1957

APPENDIX A

SYMBOLS

C_L	airplane lift coefficient, $\frac{L}{qS}$
$C_L(\alpha)$	curve defining variation of C_L with angle of attack
C_{L_t}	horizontal-tail lift coefficient, $\frac{L_t}{\eta_t q S_t}$
C_m	airplane pitching-moment coefficient about airplane center of gravity, $\frac{M_{cg}}{qS\bar{c}}$
$C_m(\alpha)$	curve defining variation of C_m with angle of attack
$(C.F.)_{\Delta\alpha}$	attitude controllability factor, $\frac{M_\delta G}{I_y \delta_{max}}$
$(C.F.)_{\Delta n'}$	load factor controllability factor, $(C.F.)_{\Delta\alpha} \frac{W}{Z_\alpha'}$
$\bar{c}$	wing mean aerodynamic chord, ft
g	acceleration of gravity, 32.2 ft/sec^2
G	effective control-system gearing, $\frac{\text{degree control-surface deflection}}{\text{degree stick deflection}}$
h_p	pressure altitude, ft
I_y	airplane pitching moment of inertia, slug-ft^2
K	parameter denoting ratio of airplane damping to that of horizontal tail damping
l_t	distance from airplane center of gravity to aerodynamic center of horizontal tail, ft
L	airplane lift, lb
L_t	horizontal-tail lift, lb

$\Delta L_{t_{\ddot{\theta}}}$ maneuvering tail-load increment, $\frac{I_Y\ddot{\theta}}{l_t}$, lb

m airplane mass, $\frac{W}{g}$, slugs

M_{cg} moment about airplane center of gravity, ft-lb

N airplane normal force, $Z(\alpha) + Z_\delta \delta$, lb

n airplane normal load factor, $\frac{N}{W}$

n' airplane normal load factor due to α, $\frac{Z(\alpha)}{W}$

q dynamic pressure, $\frac{\rho V^2}{2}$, lb/sq ft

S wing area, sq ft

S_t horizontal-tail area, sq ft

t time, sec

V airplane velocity, ft/sec

W airplane weight, lb

α airplane angle of attack, degrees or radians

γ flight-path angle, radians

δ_e elevator angle, degrees or radians

δ_s stabilizer angle, degrees or radians

δ_{stick} control-stick angle, degrees or radians

Δ increment from steady state ($n = 1.0g$) condition when preceding a symbol, unless noted otherwise

ϵ downwash angle, degrees or radians

η_t horizontal-tail efficiency factor, $\frac{q_t}{q}$

θ angle of pitch, radians

ρ mass density of air, slugs/cu ft

$\left(C_{L_\alpha}\right)_t$ horizontal-tail lift-curve slope, $\frac{dC_{L_t}}{d\alpha_t}$, per radian

$C_{L_{\delta_e}}$	$\dfrac{dC_L}{d\delta_e}$, per radian
$C_{L_{\delta_s}}$	$\dfrac{dC_L}{d\delta_s}$, per radian
C_{m_α}	$\dfrac{dC_m}{d\alpha}$, per radian
$C_{m_{\delta_e}}$	$\dfrac{dC_m}{d\delta_e}$, per radian
$C_{m_{\delta_s}}$	$\dfrac{dC_m}{d\delta_s}$, per radian
$C_{m\left(\frac{\dot{\alpha}\bar{c}}{2V}\right)}$	$\left(\dfrac{M_{\dot{\alpha}}}{qS\bar{c}}\right)\left(\dfrac{2V}{\bar{c}}\right)$, per radian
$C_{m_{\delta_{stick}}}$	$\dfrac{dC_m}{d\delta_{stick}}$, per radian
$C_{m\left(\frac{\dot{\theta}\bar{c}}{2V}\right)}$	$\left(\dfrac{M_{\dot{\theta}}}{qS\bar{c}}\right)\left(\dfrac{2V}{\bar{c}}\right)$, per radian
$M(\alpha)$	curve defining the variation of airplane pitching moment with angle of attack
$M_{\dot{\alpha}}$	$M_{\dot{\theta}_t}\left(\dfrac{\partial\epsilon}{\partial\alpha}\right)$, ft-lb/radian/sec
M_{δ_e}	$C_{m_{\delta_e}}qS\bar{c}$, ft-lb/radian
M_{δ_s}	$C_{m_{\delta_s}}qS\bar{c}$, ft-lb/radian
$M_{\delta_{stick}}$	$C_{m_{\delta_{stick}}}qS\bar{c}$, ft-lb/radian
$M_{\dot{\theta}_t}$	$\dfrac{-\eta_t\left(C_{L_\alpha}\right)_t \rho V S_t l_t^{\,2}}{2}$, ft-lb/radian/sec
$M_{\dot{\theta}}$	$KM_{\dot{\theta}_t}$, ft-lb/radian/sec
ΔM_R	magnitude of unstable break in pitching-moment curve $\Delta M(\alpha)$ (See fig. 16.)

$Z(\alpha)$	curve defining variation of airplane normal force with angle of attack
Z_{α}'	average slope of $Z(\alpha)$ versus α in pitch-up region
Z_{δ_e}	$-C_{L_{\delta_e}} qS$, lb/radian
Z_{δ_s}	$-C_{L_{\delta_s}} qS$, lb/radian
$(\dot{\ })$	equivalent notation for $\frac{d(\ )}{dt}$
$\ddot{\theta}$	equivalent notation for $\frac{d^2\theta}{dt^2}$

Subscripts

$\ddot{\theta}$	corresponding to a specified value of pitching acceleration
over	overshoot, refers to difference between peak values of $\Delta\alpha$ and Δn and values existing at time pitching-acceleration threshold attained
th	threshold
max	maximum value
rec	recovery phase of pitch-up maneuver
entry	conditions just prior to onset of pitch-up
design	design value

APPENDIX B

DERIVATION OF FACTORS RELATED TO THE PILOT'S ABILITY TO CONTROL AIRPLANE ATTITUDE AND LOAD FACTOR

From the previous discussion and examination of the equations used in the analog simulation, it appears that the controllability of pitch-up will be a function of the relationship between the airplane restoring moments and the upsetting moments. An attitude controllability factor $(C.F.)_{\Delta\alpha}$ comprised of a nondimensional grouping of terms and representing the dominating parameters may be deduced as follows:

$$(C.F.)_{\Delta\alpha} \approx \frac{\text{Restoring moments}}{\text{Upsetting moments}}$$

or

$$(C.F.)_{\Delta\alpha} \approx \frac{\begin{pmatrix}\text{Stabilizing pitching}\\ \text{moment following}\\ \text{unstable break, } M(\alpha)\end{pmatrix} + \begin{pmatrix}\text{Damping moments,}\\ M_{\dot\theta}\dot\theta + M_{\dot\alpha}\dot\alpha\end{pmatrix} + \begin{pmatrix}\text{Corrective control}\\ \text{available to pilot,}\\ M_{\delta_{stick}}(\dot\delta_{stick})_{rec}t\end{pmatrix}}{I_y\ddot\theta_{max}}$$

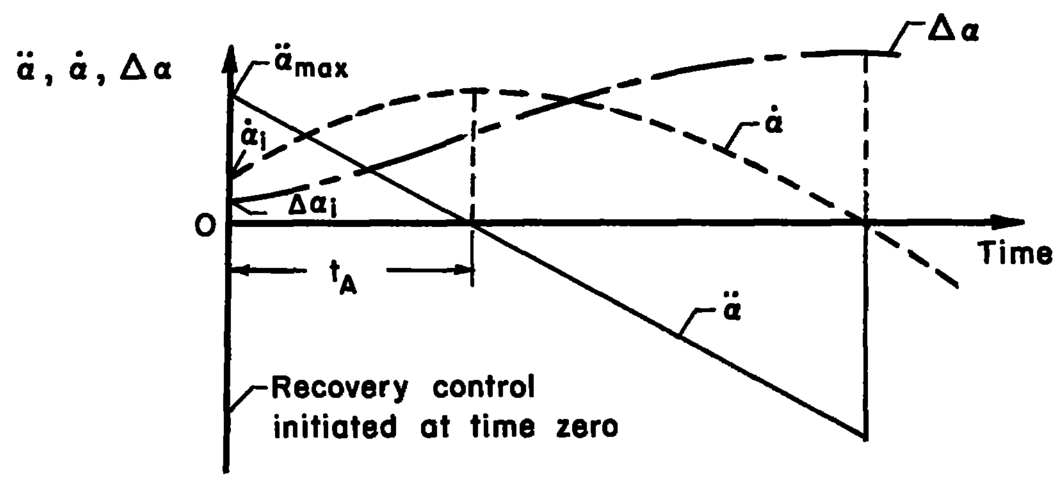
To simplify the above expression the first two terms in the numerator were neglected. A check of analog computer results indicated that the term retained $\left[M_{\delta_{stick}}(\dot\delta_{stick})_{rec}t\right]$ is generally the most important factor, particularly at the higher recovery control rates. The expression for $(C.F.)_{\Delta\alpha}$ is then defined as

$$(C.F.)_{\Delta\alpha} \approx \frac{M_{\delta_{stick}}(\dot\delta_{stick})_{rec}t}{I_y\ddot\theta_{max}}$$

This expression can be simplified still further. Since the assumption has been made that, following the application of recovery control, the damping and stability moments have a relatively small effect compared to the control moments, an equation of motion describing the airplane motions reduces to

$$\ddot\alpha = \ddot\alpha_{max} + \frac{M_{\delta_{stick}}(\dot\delta_{stick})_{rec}t}{I_y}$$

which is the equation of a straight line with intercept $\ddot{\alpha}_{max}$ and slope $M_{\delta_{stick}}(\dot{\delta}_{stick})_{rec}$. (See sketch.)



From the above sketch, the time interval required by the pilot to regain control of $\dot{\alpha}$ (or approximately $\dot{\theta}$) may be given approximately by the expression

$$t_A = \left| \frac{I_y \ddot{\alpha}_{max}}{M_{\delta_{stick}}(\dot{\delta}_{stick})_{rec}} \right|$$

or

$$t_A \approx \left| \frac{I_y \ddot{\theta}_{max}}{M_{\delta_{stick}}(\dot{\delta}_{stick})_{rec}} \right|$$

since $\ddot{\gamma}_{max}$ is relatively small. An attitude controllability factor related inversely to the time required to reduce the maximum destabilizing moment applied to the airplane to zero could then be given as

$$(C.F.)_{\Delta\alpha} \approx \frac{1}{t_A} \approx \frac{M_{\delta_{stick}}(\dot{\delta}_{stick})_{rec}}{I_y \ddot{\theta}_{max}}$$

Since pilot assessment of relative controllability on different airplanes is probably formed on the basis of fixed stick recovery control rates, the attitude controllability factor may be simplified to the final definition

$$(C.F.)_{\Delta\alpha} \approx \frac{M_{\delta_{stick}}}{I_y \ddot{\theta}_{max}}$$

To obtain a controllability factor related to airplane load factor, it is necessary to multiply $(C.F.)_{\Delta\alpha}$ by W/Z_α'.

APPENDIX C

ESTIMATION OF CONTROLLABILITY FACTORS AND AIRPLANE ANGLE OF ATTACK AND LOAD-FACTOR OVERSHOOTS

In figure 14, a relationship between the computed controllability factors $(C.F.)_{\Delta\alpha}$ and $(C.F.)_{\Delta n'}$ and the computed angle of attack and load-factor overshoots is given. The results are presented for fixed stick recovery control rates and include data for all three entry rates considered and for both an altitude of 35,000 feet and the altitude corresponding to entry into the pitch-up region in a 6g maneuver. These data were taken primarily from the results in figure 15 which shows the effects of entry rate and altitude on the attitude and load-factor controllability factors. The load-factor overshoots presented include only that portion due to $Z(\alpha)$. The effects of $Z_\delta\Delta\delta$ are not included. In order to estimate values of C.F. and overshoot without performing the actual simulator studies, it is first necessary to determine values of $\ddot{\theta}_{max}$. Figure 16 presents a variation of computed values of $\ddot{\theta}_{max}$ (taken from the REAC studies on five of the six reference airplanes) with values estimated by the procedure shown in the sketch in figure 16. Results are again given for all three entry rates considered and for altitudes of 35,000 feet and that corresponding to entry into the pitch-up in a 6g maneuver. These results suggest that $\ddot{\theta}_{max}$ can be estimated from wind-tunnel pitching-moment data by the procedure indicated in the sketch in figure 16. If I_y and $M_{\delta_{stick}}$ are known, values of $(C.F.)_{\Delta\alpha}$ and $(C.F.)_{\Delta n'}$ may then be computed and the angle of attack and load-factor overshoots corresponding to these estimated controllability factors may be determined by referring to the plots presented in figure 14. For cases where $M_{\delta_{stick}}$ varies with stick deflection, the appropriate value of $M_{\delta_{stick}}$ to use is that corresponding to the deflection required to maneuver to point A in figure 16. (It should also be noted that for airplanes which do not have constant M_δ with α, this procedure does not appear to be applicable).

Since an inspection of the computed results indicated that $\ddot{\theta}_{th}$ was generally attained at about the angle of attack where the local C_{m_α} first becomes zero (point A in the sketch on fig. 16), the peak angles of attack and load factor may be determined by adding the overshoots to the values at this angle of attack.

It should be pointed out that this procedure for estimating values of controllability factor and overshoot assumes that $\ddot{\theta}_{max}$ is dependent only on entry rate and is invariant with recovery control rate for a given pitching-moment curve $M(\alpha)$. Analog results for the six airplanes considered in the present study (figs. 4 and 7) appear to justify this assumption.

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2. Sadoff, Melvin, Matteson, Frederick H., and Havill, C. Dewey: A Method for Evaluating the Loads and Controllability Aspects of the Pitch-Up Problem. NACA RM A55D06, 1955.

3. Sadoff, Melvin, Matteson, Frederick H., and Van Dyke, Rudolph D., Jr.: The Effect of Blunt-Trailing-Edge Modifications on the High-Speed Stability and Control Characteristics of a Swept-Wing Fighter Airplane. NACA RM A54C31, 1954.

4. Anderson, Seth B.: Correlation of Flight and Wind-Tunnel Measurements of Roll-Off in Low-Speed Stalls on a 35° Swept-Wing Aircraft. NACA RM A53G22, 1953.

5. Budish, Nathan N.: Longitudinal Stability at High Airspeeds. (Model XB-47). Document No. D-8603, Boeing Airplane Co., Feb. 29, 1952.

TABLE I.- PHYSICAL CHARACTERISTICS OF THE SIX AIRPLANES

Item \ Aircraft	F-86A (both unmodified and with blunt trailing-edge ailerons)	F-84F (elevator-control configuration)	YF-86D (high-tail configuration)	F-86F (6-3 leading-edge configuration)	F-100A ("D" configuration)	B-47
Wing						
Total area, sq ft	287.9	325	287.9	302.3	385.2	1428
Span, ft	37.1	33.6	37.1	37.1	38.6	116
Mean aerodynamic chord, ft	8.08	10	8.08	8.48	11.17	12.99
Aspect ratio	4.79	3.47	4.79	4.55	3.86	9.43
Taper ratio	0.51	0.579	0.51	0.51	0.262	0.42
Sweepback of 25-percent chord line, deg	35.23	40	35.23	35	45	35
Horizontal tail						
Total area, sq ft	34.99	55.8	53.9	34.9	98.9	268
Span, ft	12.75	14.1	16.6	12.8	18.78	33
Maximum stabilizer or elevator deflection, deg	-35 to +15	-27.5 to +15	-15 to +8	-21 to +7	-25 to +5	-25 to +15
Control stick to control surface gearing	1:1	1:1.195	[a]1:1	[a]1:0.65	[a]1:1.39	1:1.3
Tail length, horizontal, ft	18.25	19.8	15.7	18.25	14.1	46.5
Airplane weight, lb	12,400	16,400	14,100	13,000	24,000	115,000
Airplane mass, slugs	385	508	438	403	745	3,575
Airplane moment of inertia in pitch, slug-ft^2	17,480	33,300	27,000	18,200	58,100	1,480,000
Center of gravity, percent $\bar{c}$	22.5	21.5	21.5	25.9	30	25

[a]For these cases where the control gearing varied with stick deflection, the values given are approximately those for the stick deflection just prior to application of forward (recovery) deflections.

TABLE II.- AERODYNAMIC CHARACTERISTICS OF THE SIX AIRPLANES

Characteristic \ Airplane	F-86A (unmodified and blunt trailing-edge aileron configuration)	F-84F (elevator-control configuration)	YF-86D (high-tail configuration)	F-86F (6-3 leading-edge configuration)	F-100A ("D" configuration)	B-47
$C_m(\alpha)$	Figure 3	Figure 3	Figure 3	Figure 3	Figure 3	Figure 3
$C_L(\alpha)$	Figure 3	Figure 3	Figure 3	Figure 3	Figure 3	Figure 3
$-C_{m_\delta}$	0.246	0.273	1.09	0.891	0.686	1.26
C_{L_δ}	0.109	0.138	0.560	0.414	0.546	0.832
$-C_{m_{\left(\frac{\dot{\theta}\bar{c}}{2V}\right)}}$	4.69	7.84	6.15	4.05	5.29	22.5
$-C_{m_{\left(\frac{\dot{\alpha}\bar{c}}{2V}\right)}}$	0.83	3.44	1.08	0.714	1.91	5.64

TABLE III.- QUESTIONNAIRE FOR PILOT PITCH-UP RATING

I Is pitch-up region useful at all for maneuvering? Yes or No.

II Consider the following situations:

A. If you are tracking a target airplane and enter the pitch-up region, what is your assigned rating of your ability to return to or remain on the correct flight path to continue the tracking?

B. If you have entered the pitch-up region during a gunnery run, what rating would you give the airplane as a gun platform in the pitch-up region?

C. If rating for A and B is poor, is reason other than insufficient or inadequate controllability?

D. How would you rate this airplane with regard to the tendency for a pilot to apply rapid and perhaps excessive control during pitch-up recoveries?

III Rate the pitch-up according to abruptness. (What is response quantity which you feel is related to the abruptness of pitch-up?)

IV Rate the pitch-up according to overshoot load factor. (What is your definition of overshoot load factor?)

V What rating do you assign the airplane with regard to how much pitch-up restricts or limits maneuverability of the airplane?

TABLE IV.- PILOT RATING SCHEDULE FOR PITCH-UP

Rating	Category	Description
0	Satisfactory	Satisfies stability and control requirements.
1 2	Marginally Satisfactory	Pitch-up barely perceptible. Does not appreciably diminish usefulness of the airplane in performing a desired task. Abruptness of airplane response and overshoot in attitude or load factor during pitch-up not much increased over comparable satisfactory airplane. Little tendency for the pilot to apply rapid and excessive corrective control.
3 4 5	Unsatisfactory but Acceptable	Pitch-up is more apparent. More or less difficulty experienced in performing the desired task. Abruptness of airplane motion and overshoot in attitude or load factor during pitch-up considerably increased over that for marginally satisfactory airplane. There may be some tendency for the pilot to apply rapid and perhaps excessive corrective control.
6 7 8	Unsatisfactory	Pitch-up severe ranging from controllable only with the greatest difficulty to practically uncontrollable. Abruptness of airplane motions during pitch-up approaching degree where pilot feels he has little or no control over the overshoots in attitude or load factor, which are relatively large. Increased tendency for the pilot to apply rapid and excessive corrective control.
9 10	Unacceptable	Pitch-up so severe that airplane is uncontrollable. The abruptness of the airplane motions and the magnitude of the overshoots are so extreme, even at high altitude, that the pilot would not consider approaching the pitch-up boundary because of concern for the structural integrity of the airplane. Some possibility of entering into a spin or other unusual maneuver from which recovery may be difficult or impossible.

TABLE V.- SUMMARY OF PILOT "A" PITCH-UP RATINGS

Item \ Airplane	F-86A	F-86A mod.	F-84F	YF-86D	F-86F	F-100A	B-47
I	No	Yes, marg.	No	Yes	Yes	Yes	Yes
II(A)	8	6	7	3	4	3	2
II(B)	8	7	8	6	6	3	Not rated
II(C)	No	No	No	No	No	No	Not rated
II(D)	8	7	7	5	6	2	Not rated
III	8	6	8	6	7	3	2
IV	8	7	6	5	7	4	2
V	8	6	7	4	4	2	2

TABLE VI.- SUMMARY OF PITCH-UP RATINGS FOR PILOTS B TO F

		Airplane						
Item	Pilot	F-86A basic	F-86A mod.	F-84F	YF-86D	F-86F	F-100A	B-47
I	B	No	-	No	Yes	Yes	-	-
	C	-	-	No	-	-	-	-
	D	-	No	No	-	No	No	No
	E	-	-	-	-	No	-	No
	F	-	-	No	-	No	-	-
II(A)	B	8	-	9	4	5-6	-	-
	C	-	-	9	-	-	-	-
	D	-	4	8	-	4	2-3	2-3
	E	-	-	-	-	3	-	2
	F	-	-	4-5	-	2-3	-	-
II(B)	B	9	-	10	7	8	-	-
	C	-	-	9	-	-	-	-
	D	-	8	6	-	8	2-3	6
	E	-	-	-	-	6	-	5
	F	-	-	4-5	-	2-3	-	-
II(C)	B	No	-	No	No	Not rated	-	-
	C	-	-	No	-	-	-	-
	D	-	No	No	-	No	No	No
	E	-	-	-	-	No	-	No
	F	-	-	No	-	No	-	-
II(D)	B	2-3	-	1	4	7	-	-
	C	-	-	9	-	-	-	-
	D	-	2-3	5-6	-	2-3	1	1
	E	-	-	-	-	4	-	1
	F	-	-	4-5	-	2-3	-	-
III	B	7	-	8	4	7-8	-	-
	C	-	-	10	-	-	-	-
	D	-	4	5	-	4	1	2
	E	-	-	-	-	4	-	1
	F	-	-	5	-	3	-	-
IV	B	7	-	6	3	5	-	-
	C	-	-	8	-	-	-	-
	D	-	6	7	-	6	1	2
	E	-	-	-	-	4	-	3
	F	-	-	5	-	3	-	-
V	B	8	-	9	5	5	-	-
	C	-	-	9	-	-	-	-
	D	-	8	9	-	8	2	2
	E	-	-	-	-	5	-	3
	F	-	-	4-5	-	2-3	-	-

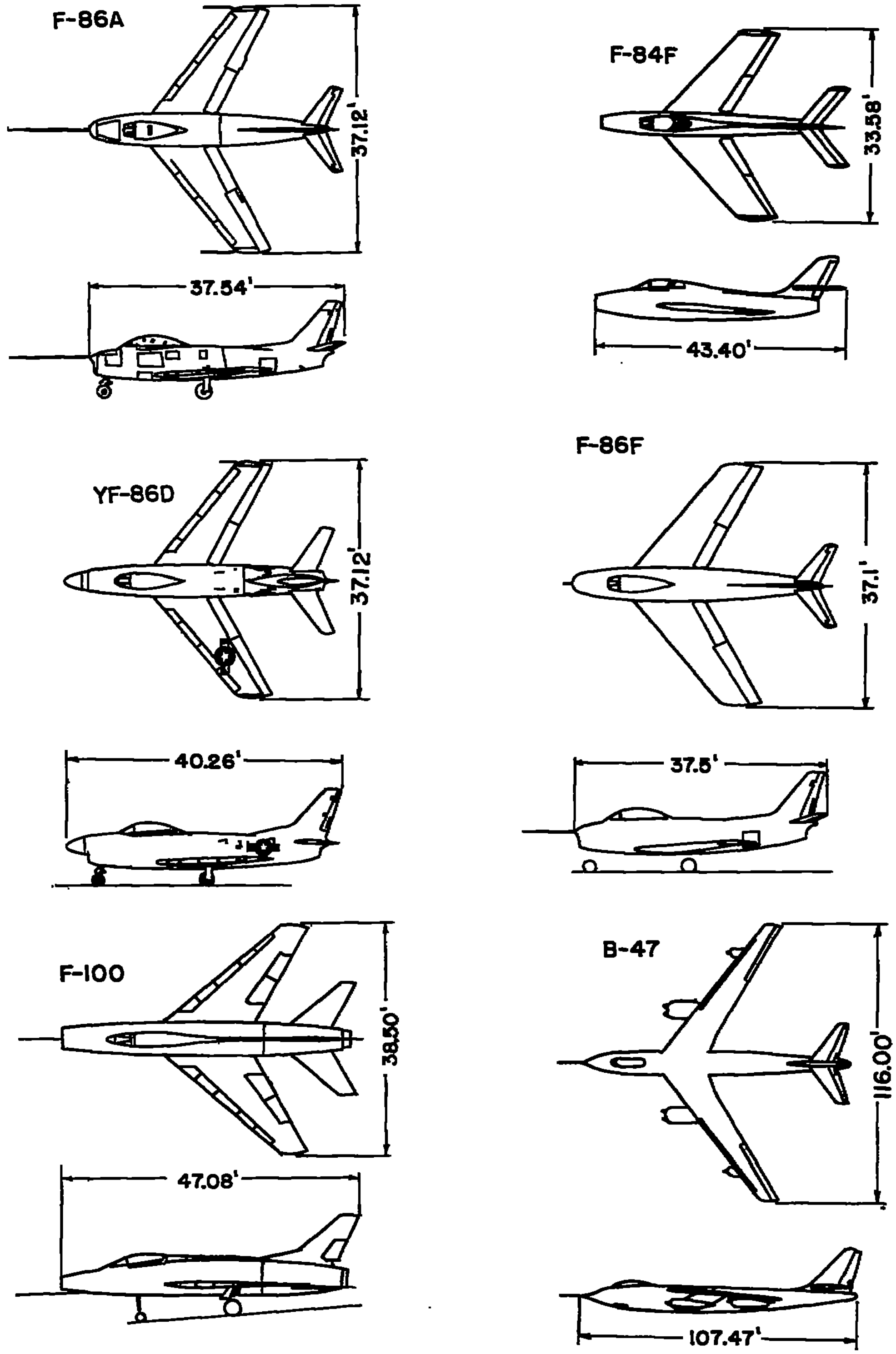


Figure 1.- Two-view drawings of the six airplanes considered in the present study.

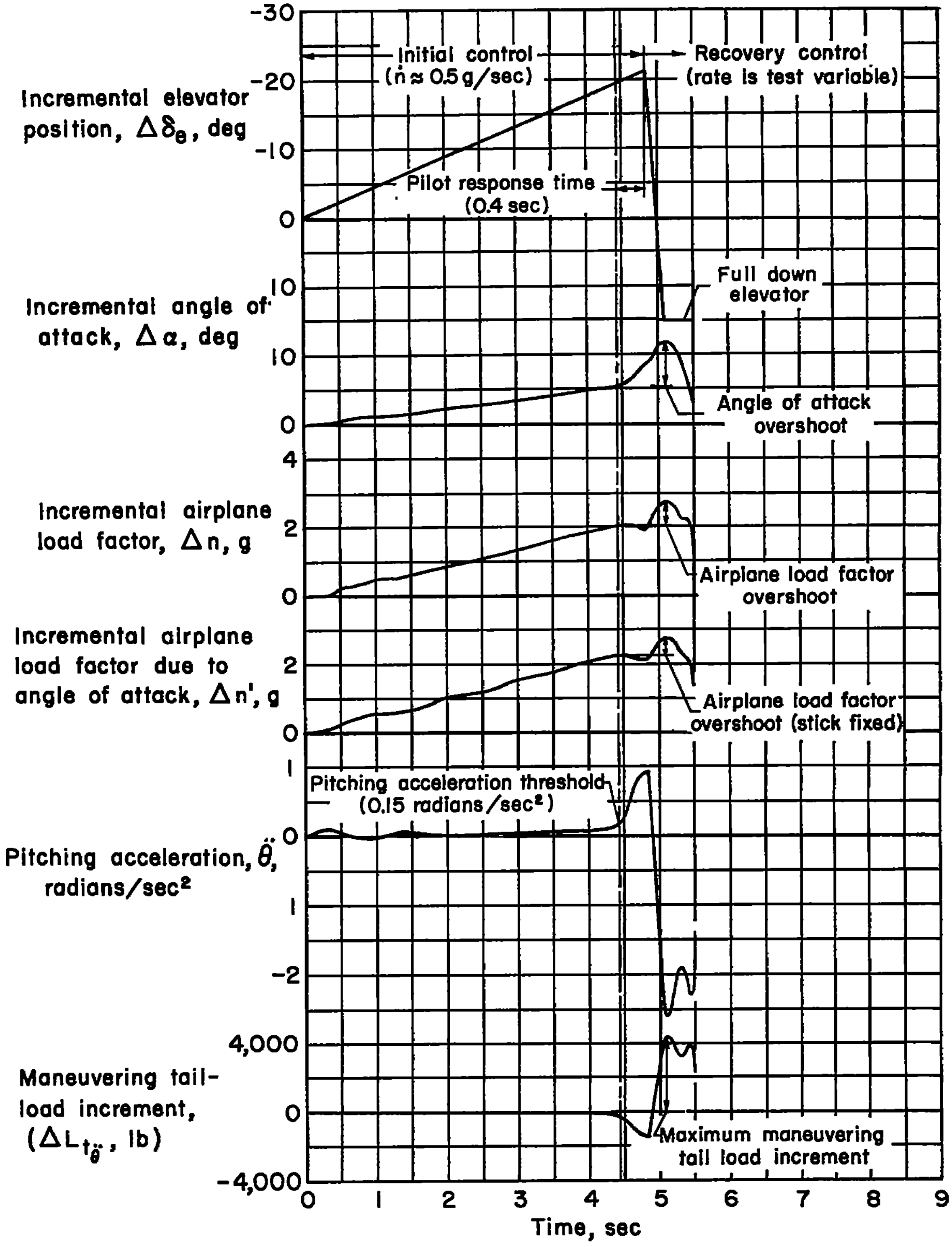


Figure 2.- Time history of standard pitch-up maneuver as applied to the F-84F airplane at 0.90 Mach number and 35,000 feet.

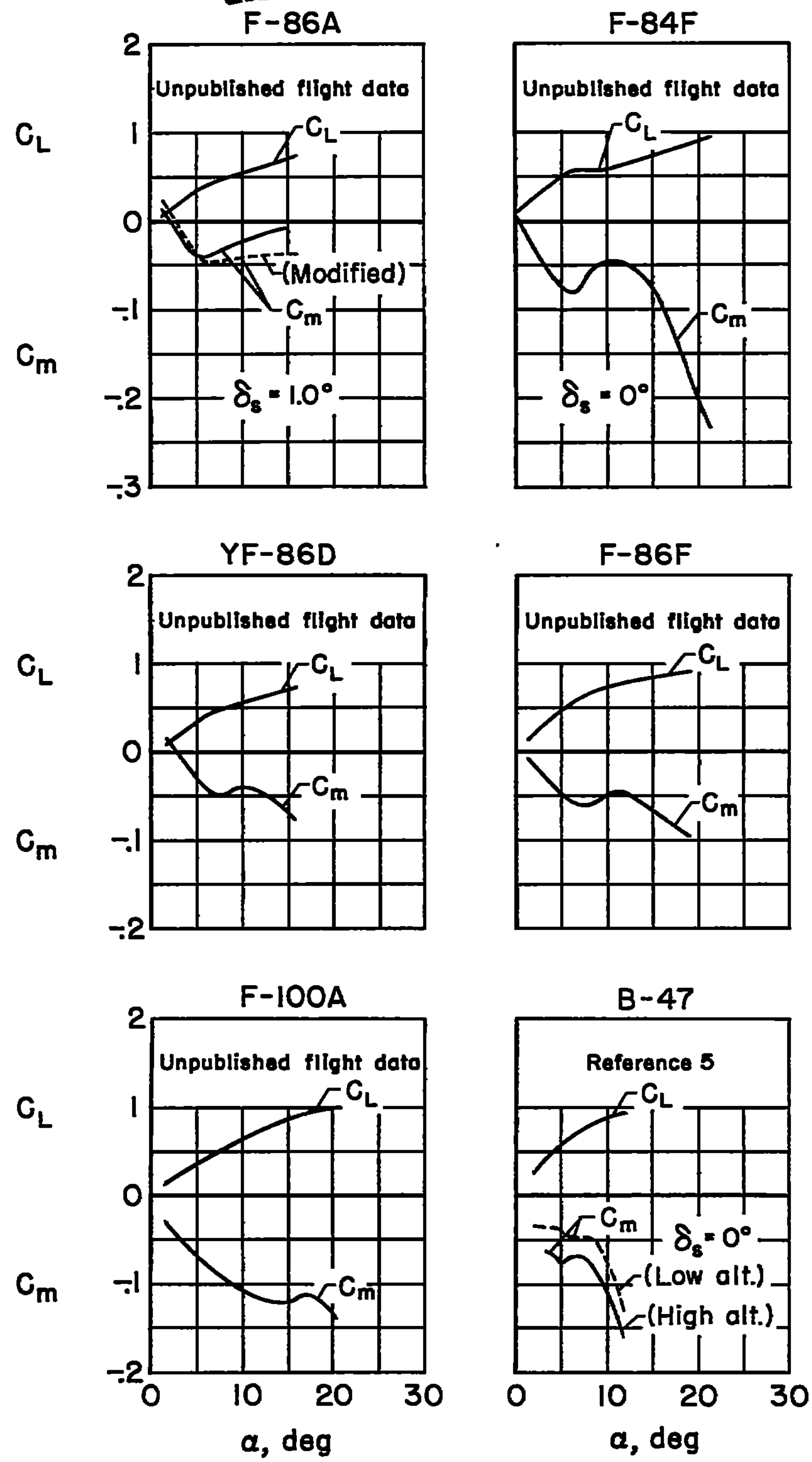
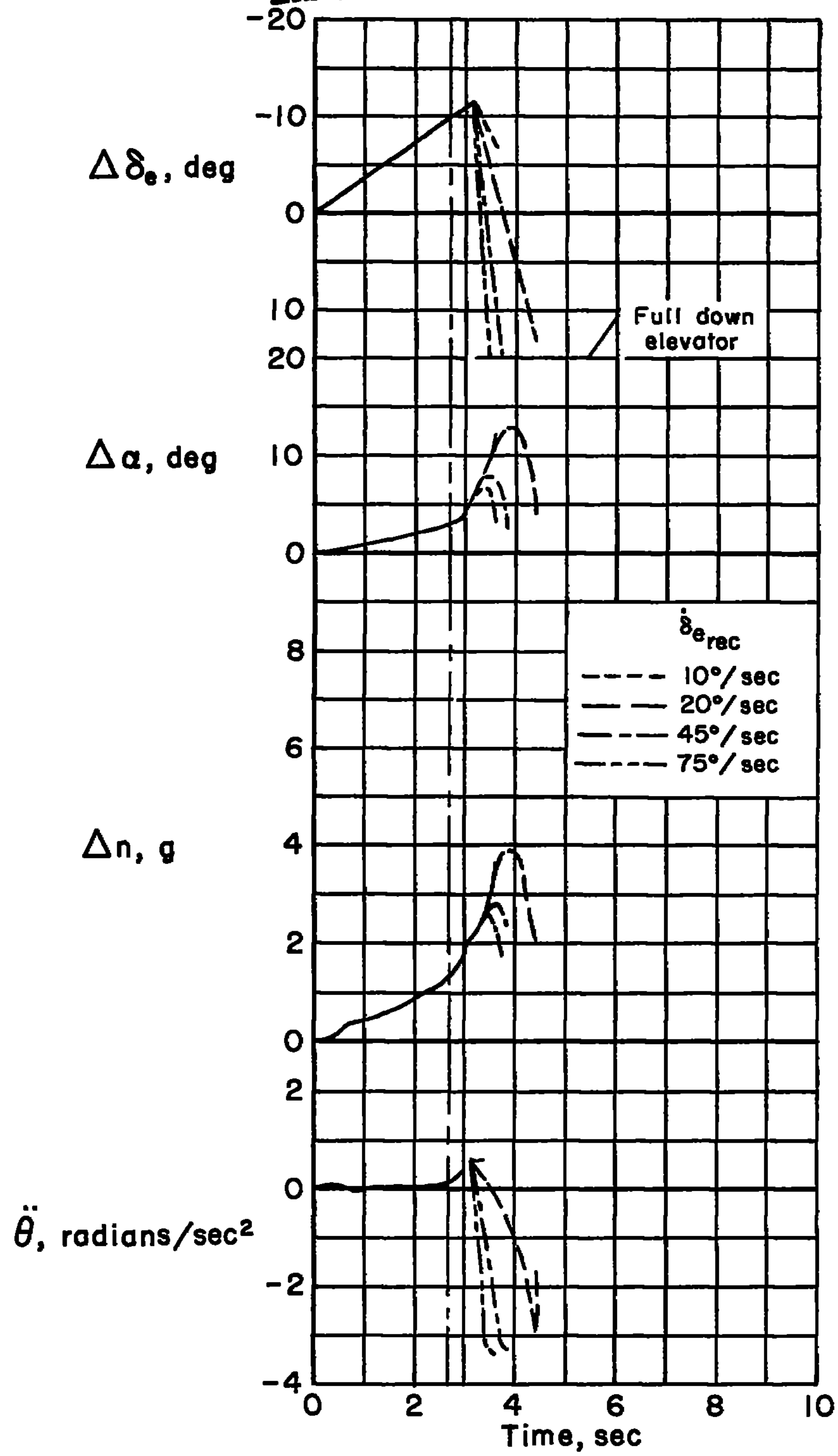
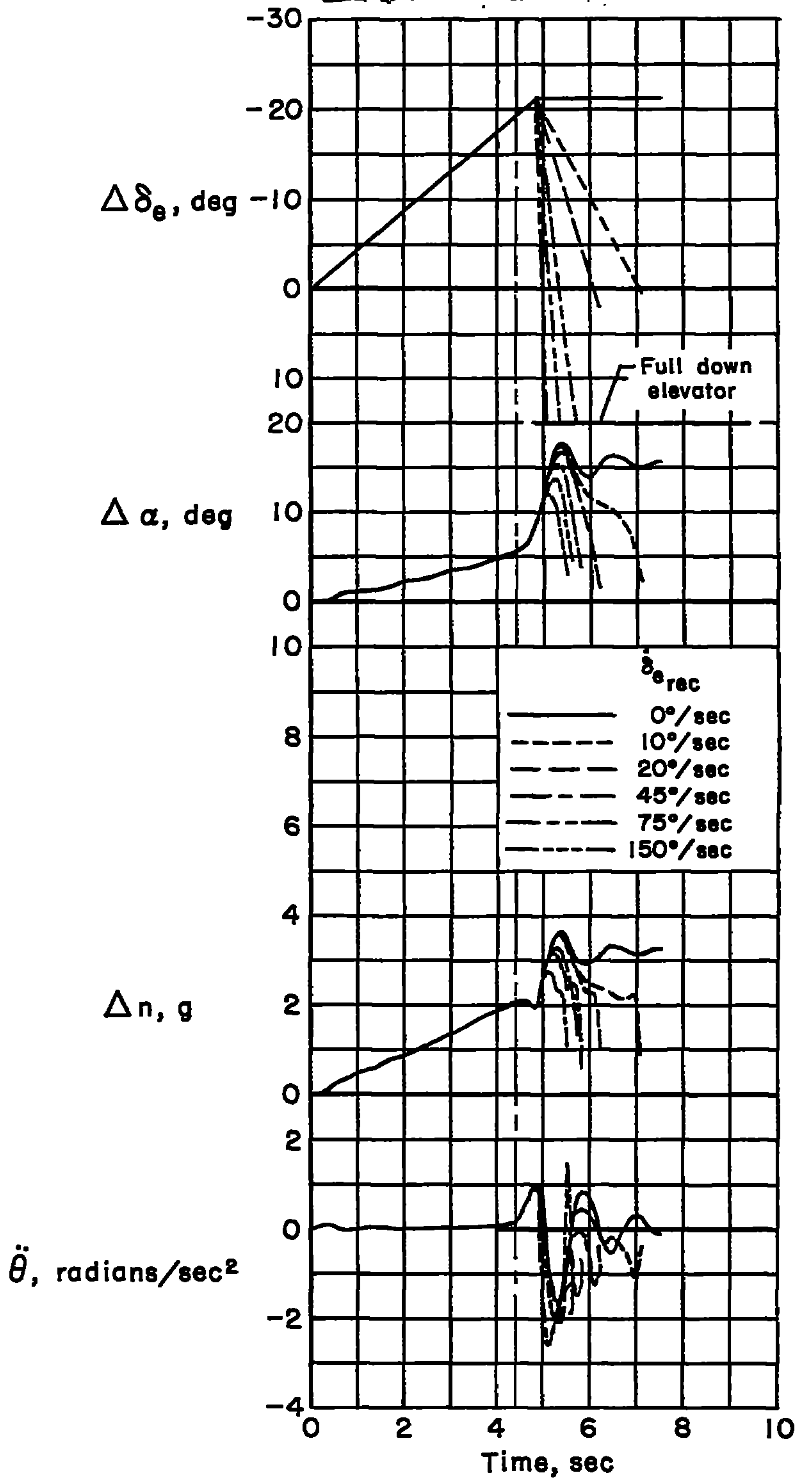


Figure 3.- The variation of lift and pitching-moment coefficients with angle of attack for the six airplanes.



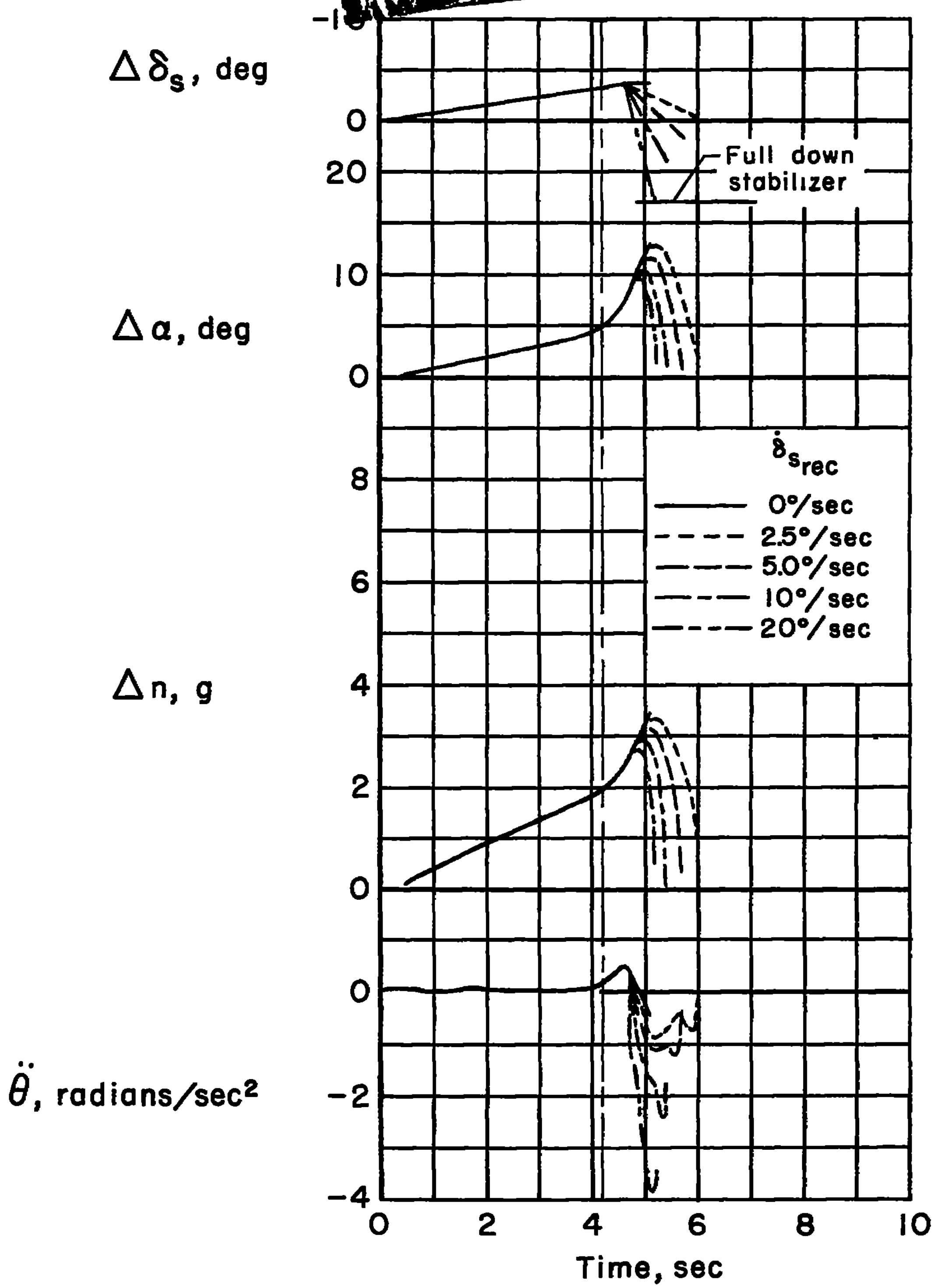
(a) F-86A; Δn_{entry} = 1.5g

Figure 4.- Computed time histories of pitch-up maneuvers at 35,000 feet; $\dot{n}_{entry}$ = 0.5g/second; $n_{entry} \approx$ 35- to 55-percent n_{design}.



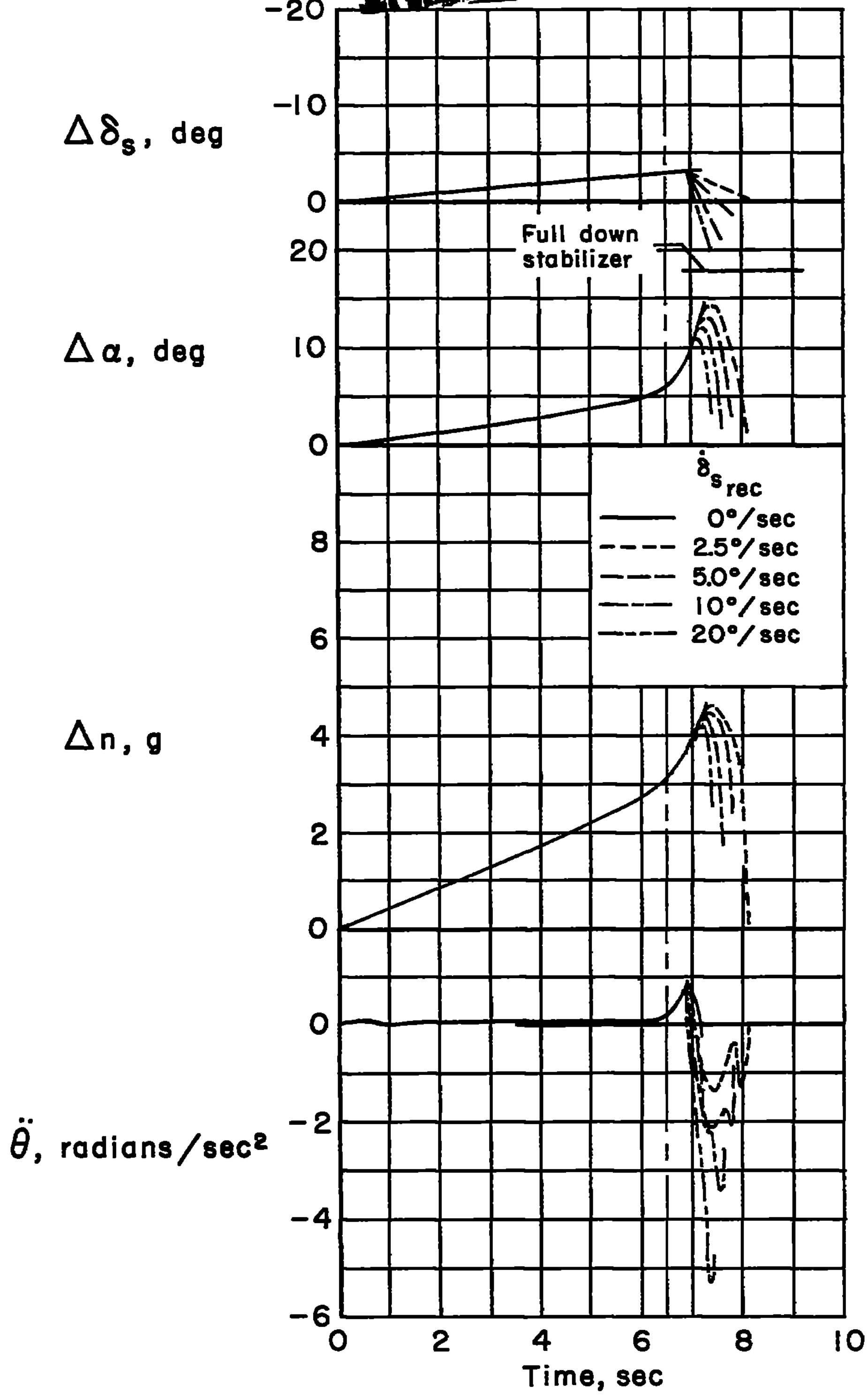
(b) F-84F; Δn_{entry} = 2.0g

Figure 4.- Continued.



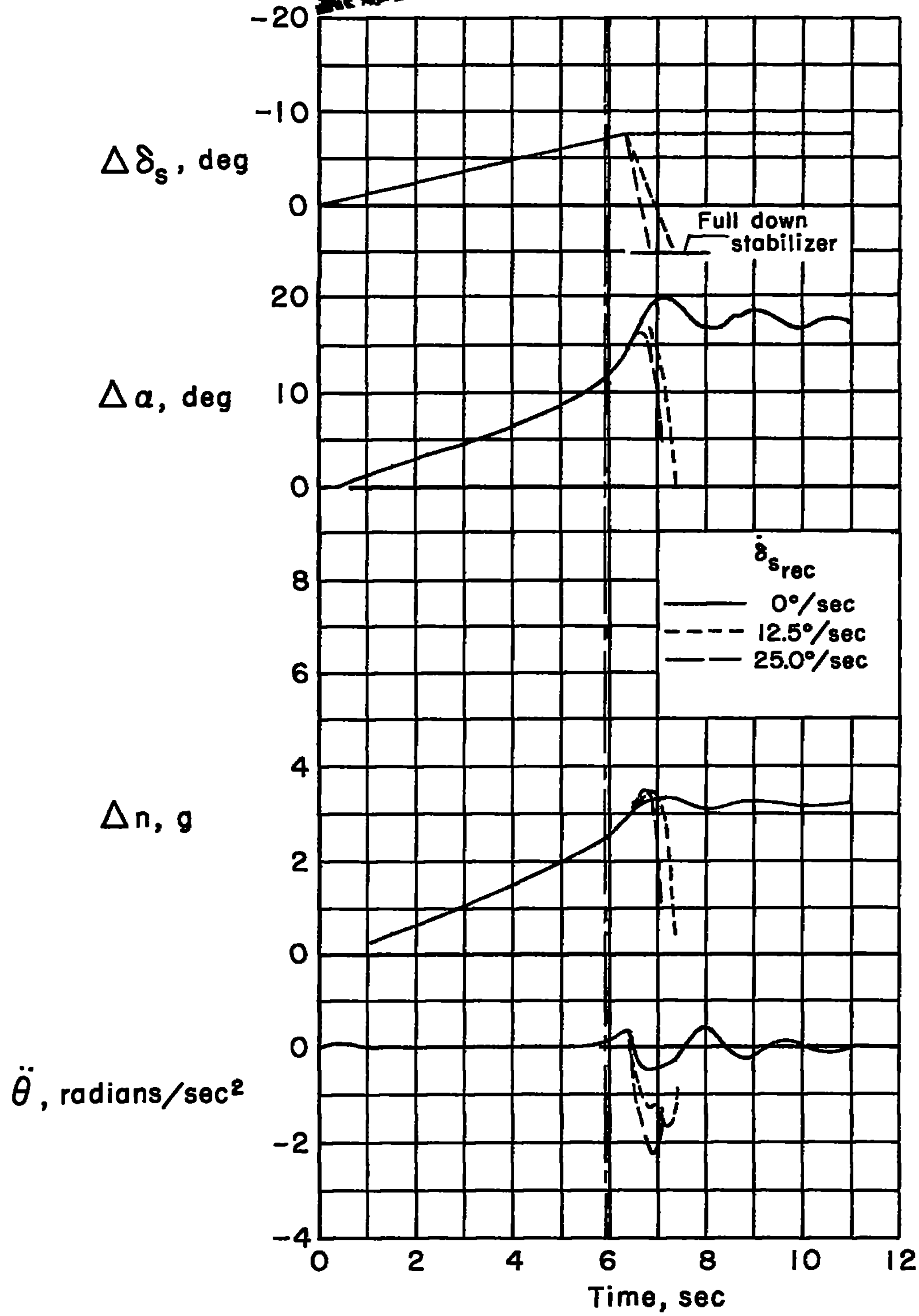
(c) YF-86D; $\Delta n_{entry} = 1.9g$

Figure 4.- Continued.



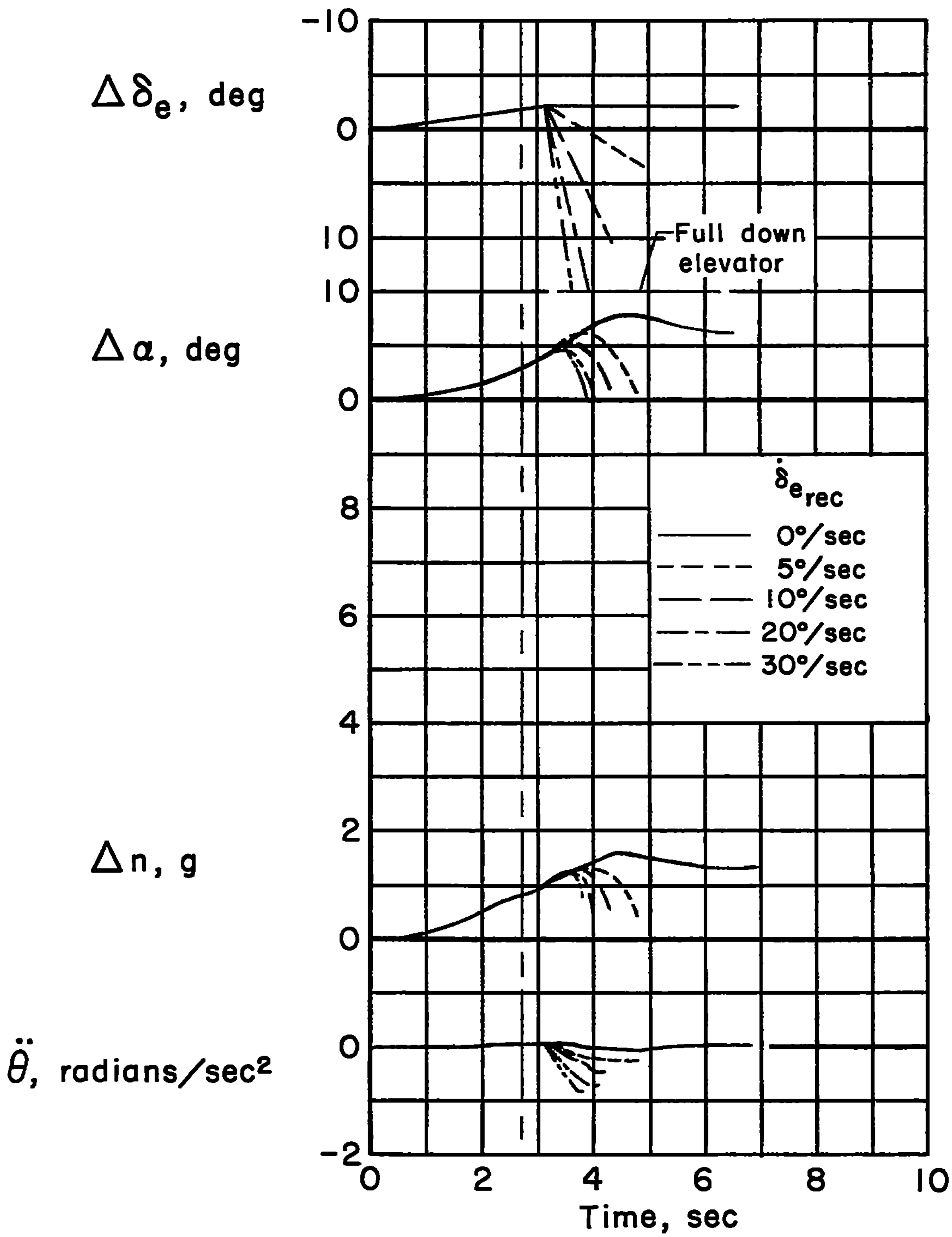
(d) F-86F; Δn_{entry} = 3.1g

Figure 4.- Continued.



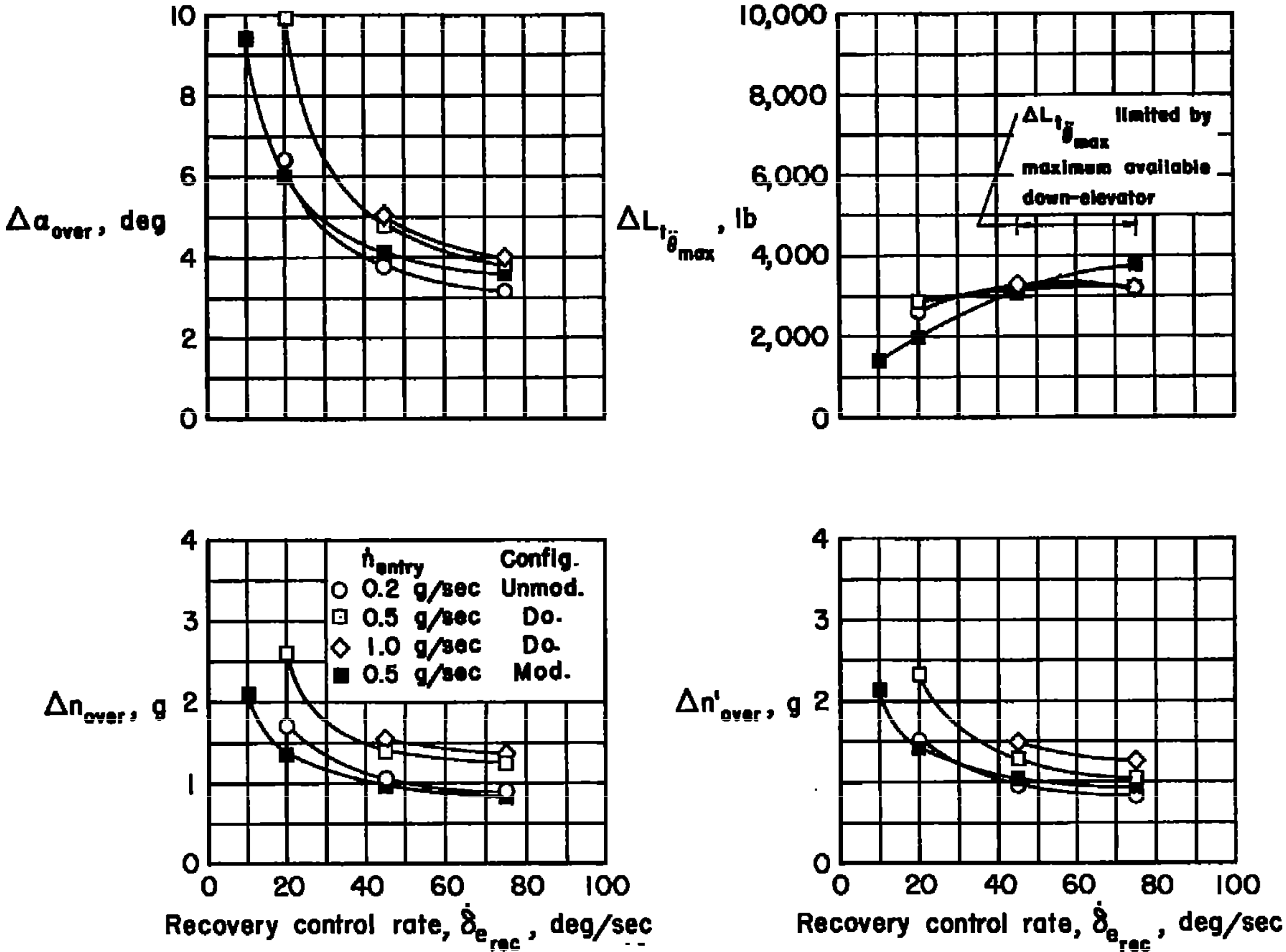
(e) F-100A; Δn_{entry} = 2.4g

Figure 4.- Continued.



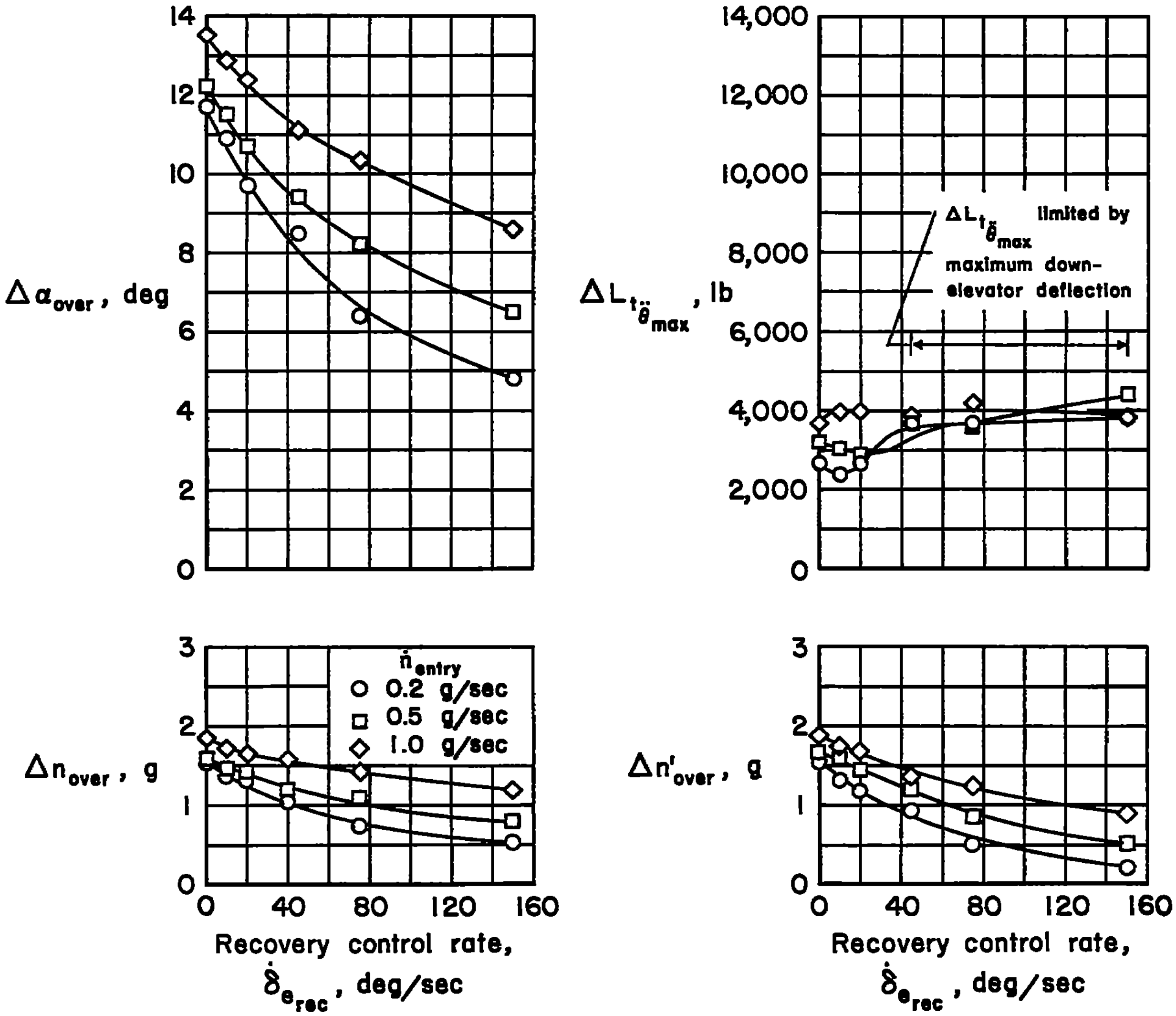
(f) B-47; Δn_{entry} = 0.7g

Figure 4.- Concluded.



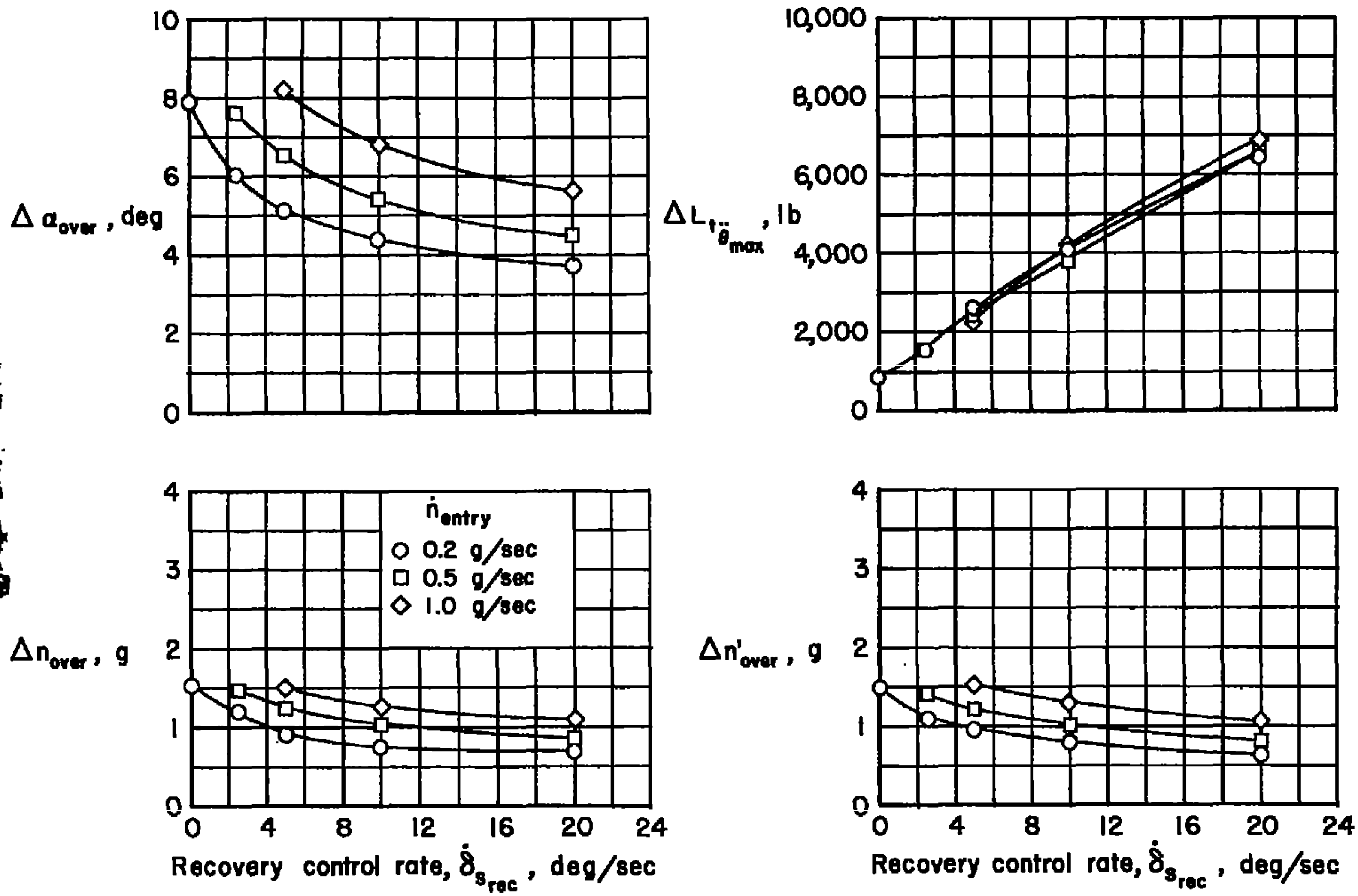
(a) F-86A; $\Delta n_{entry} = 1.5g$

Figure 5.- Variation of the computed overshoots in angle of attack and load factor and of the maneuvering tail-load increment with recovery control rate at 35,000 feet for several entry rates; $n_{entry} \approx$ 35- to 55-percent n_{design}.



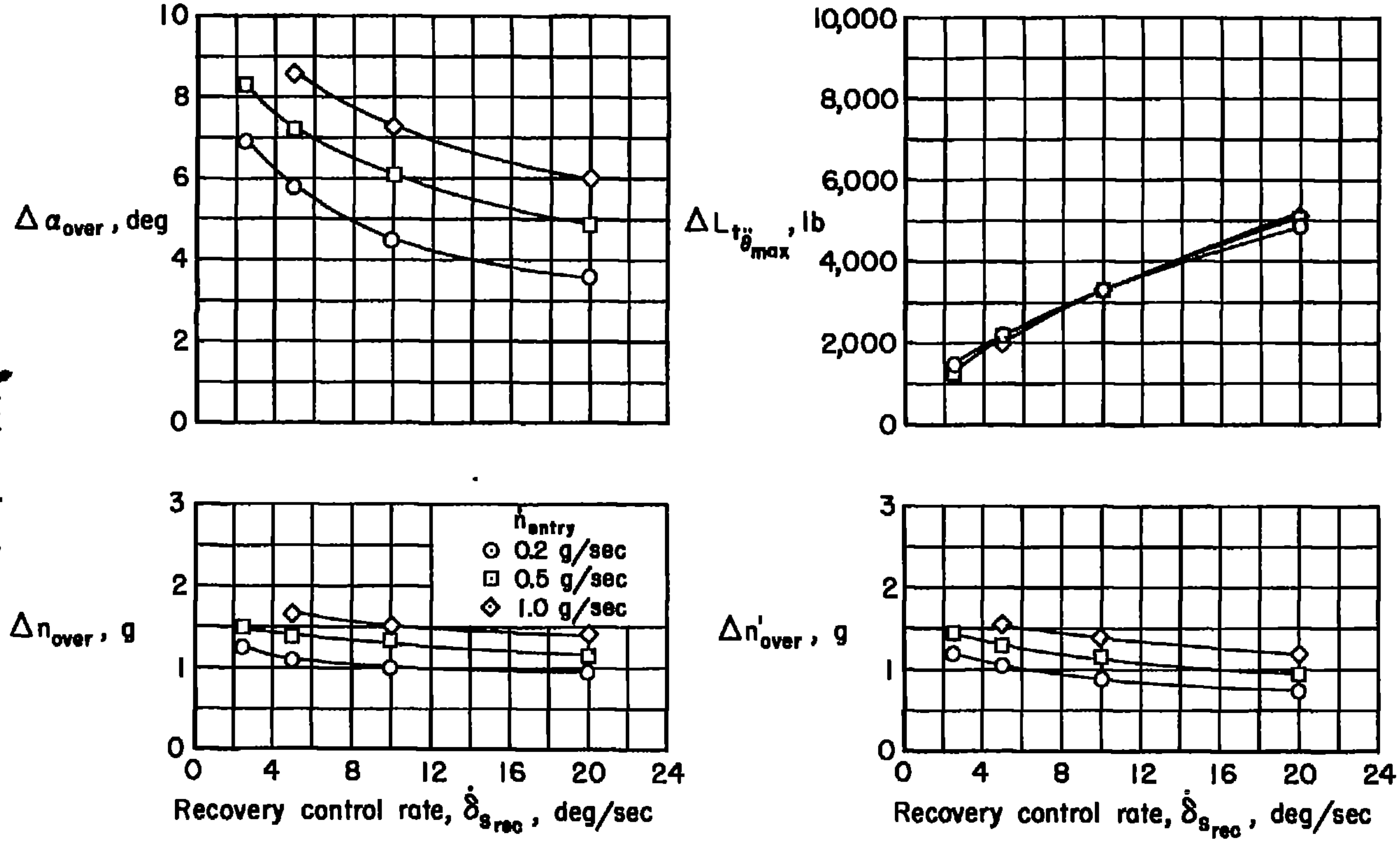
(b) F-84F; Δn_{entry} = 2.0g

Figure 5.- Continued.



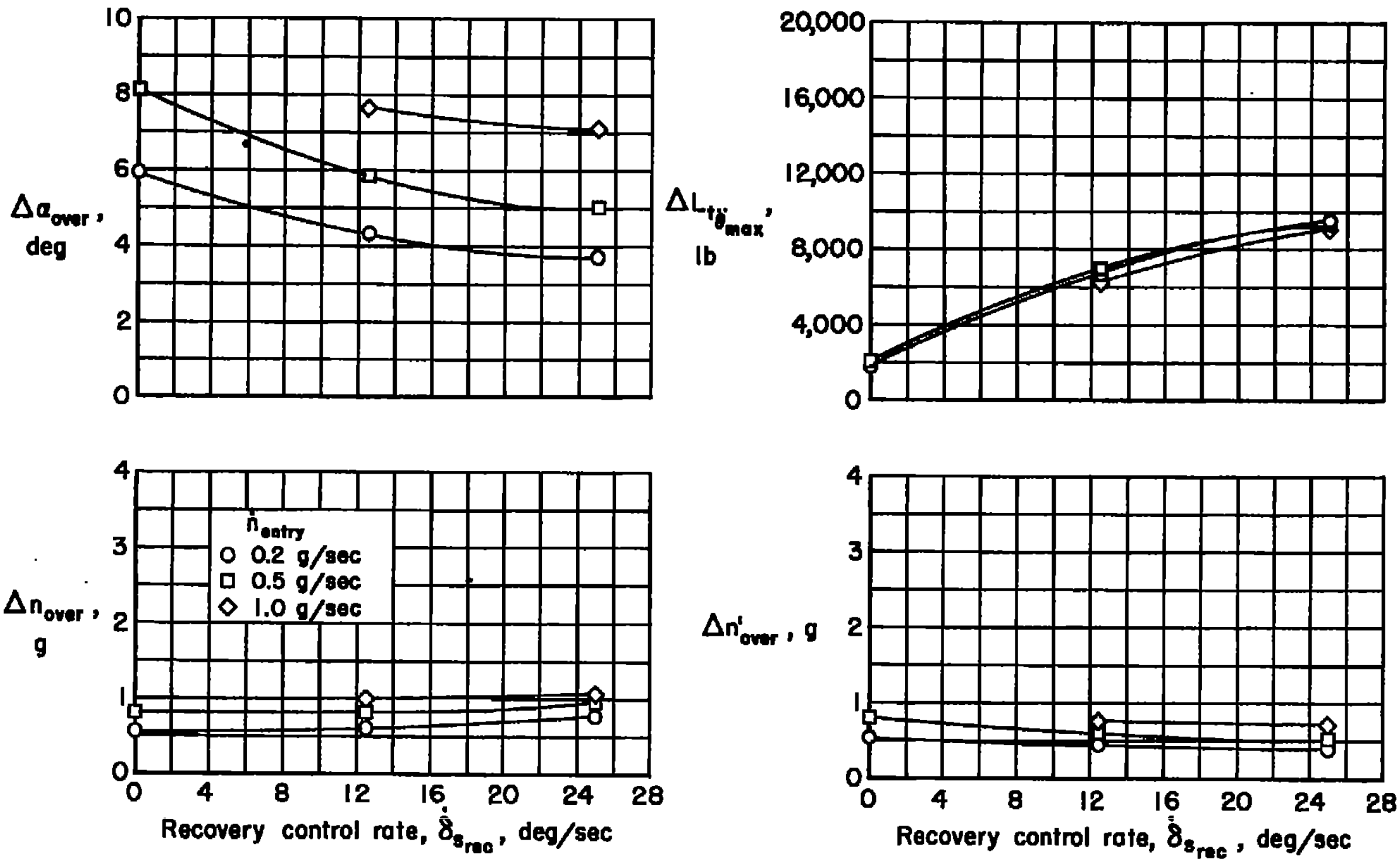
(c) YF-86D; Δn_{entry} = 1.9g

Figure 5.- Continued.



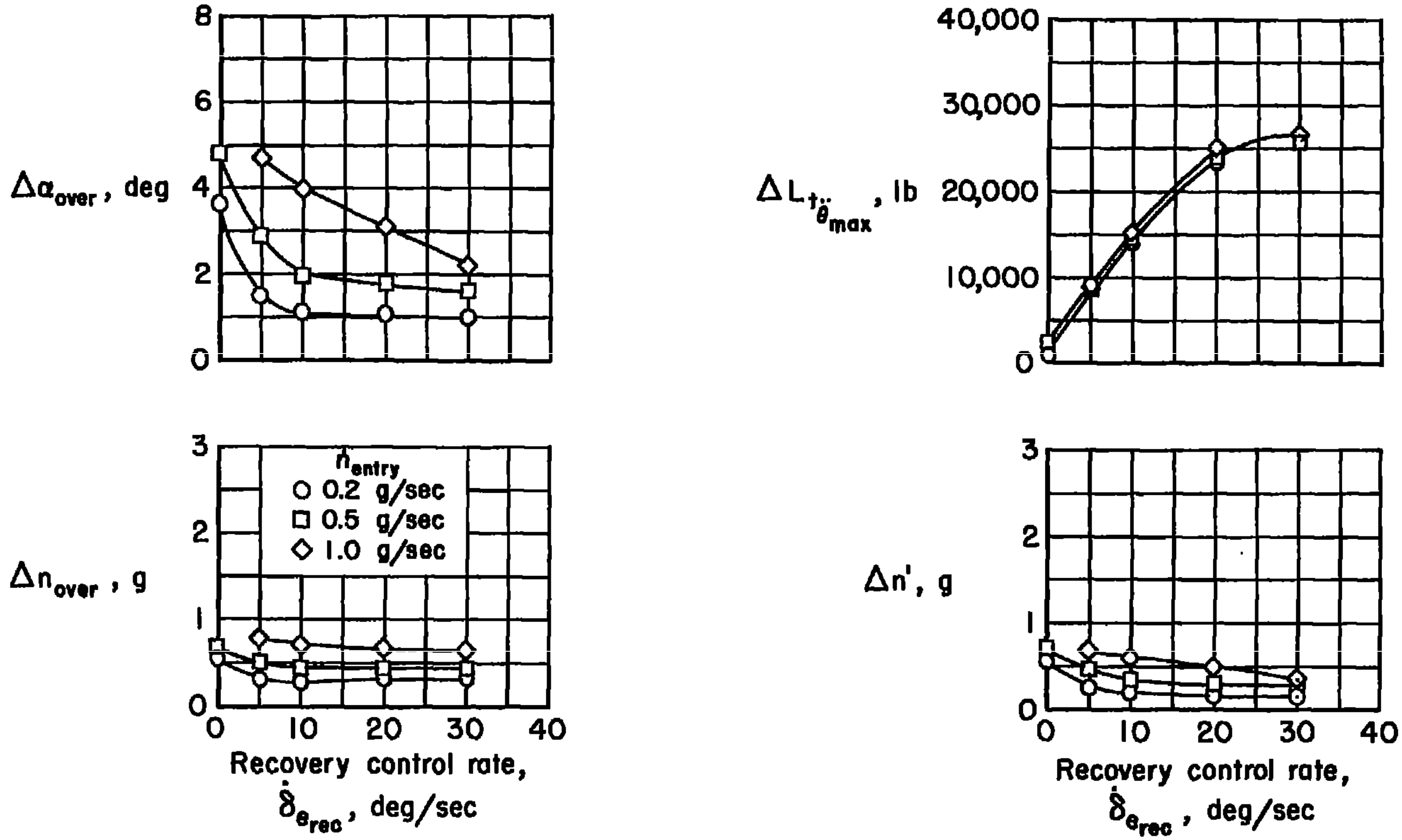
(d) F-86F; Δn_{entry} = 3.1g

Figure 5.- Continued.



(e) F-100A; Δn_{entry} = 2.4g

Figure 5.- Continued.



(f) B-47; Δn_{entry} = 0.7g

Figure 5.- Concluded.

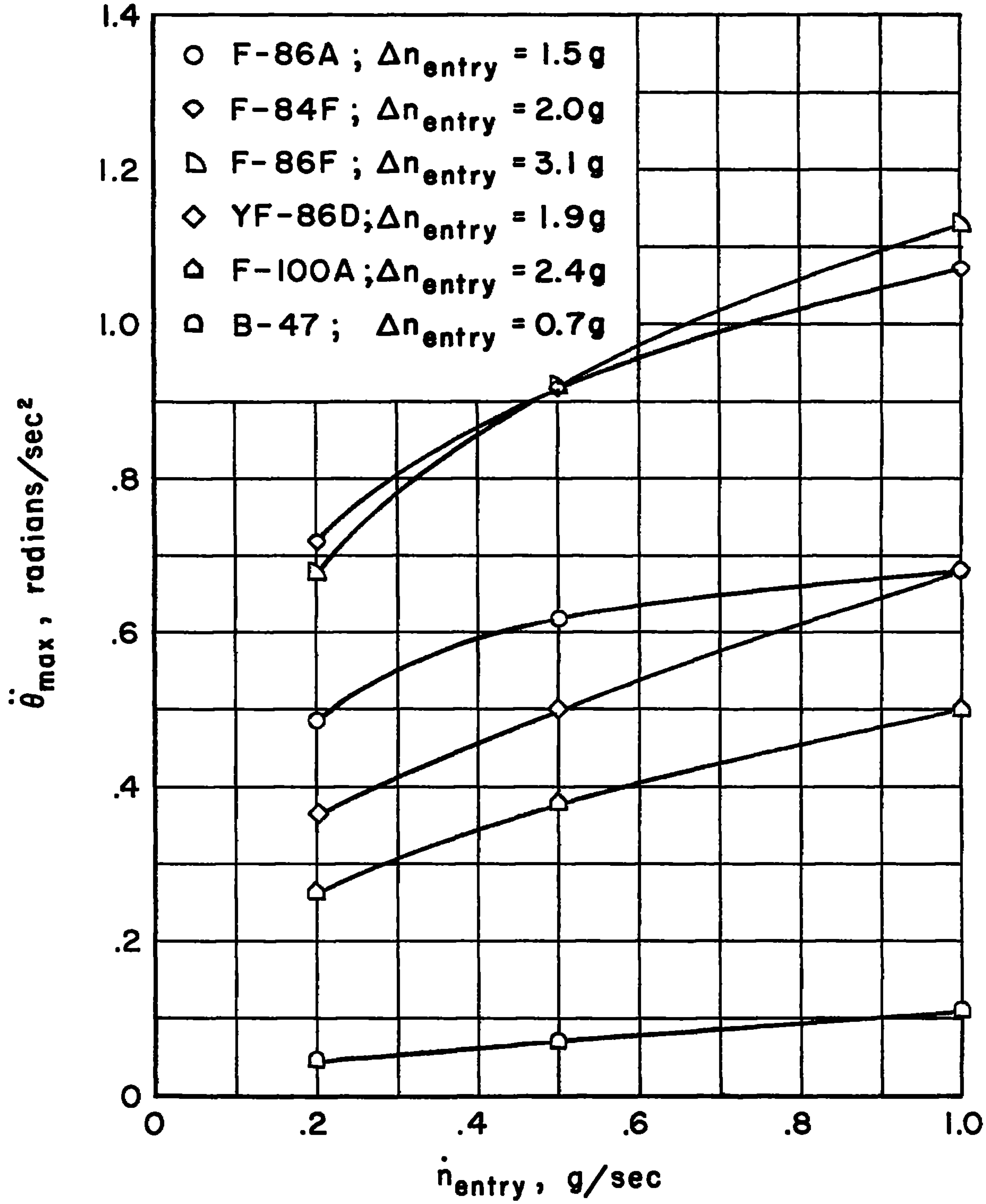
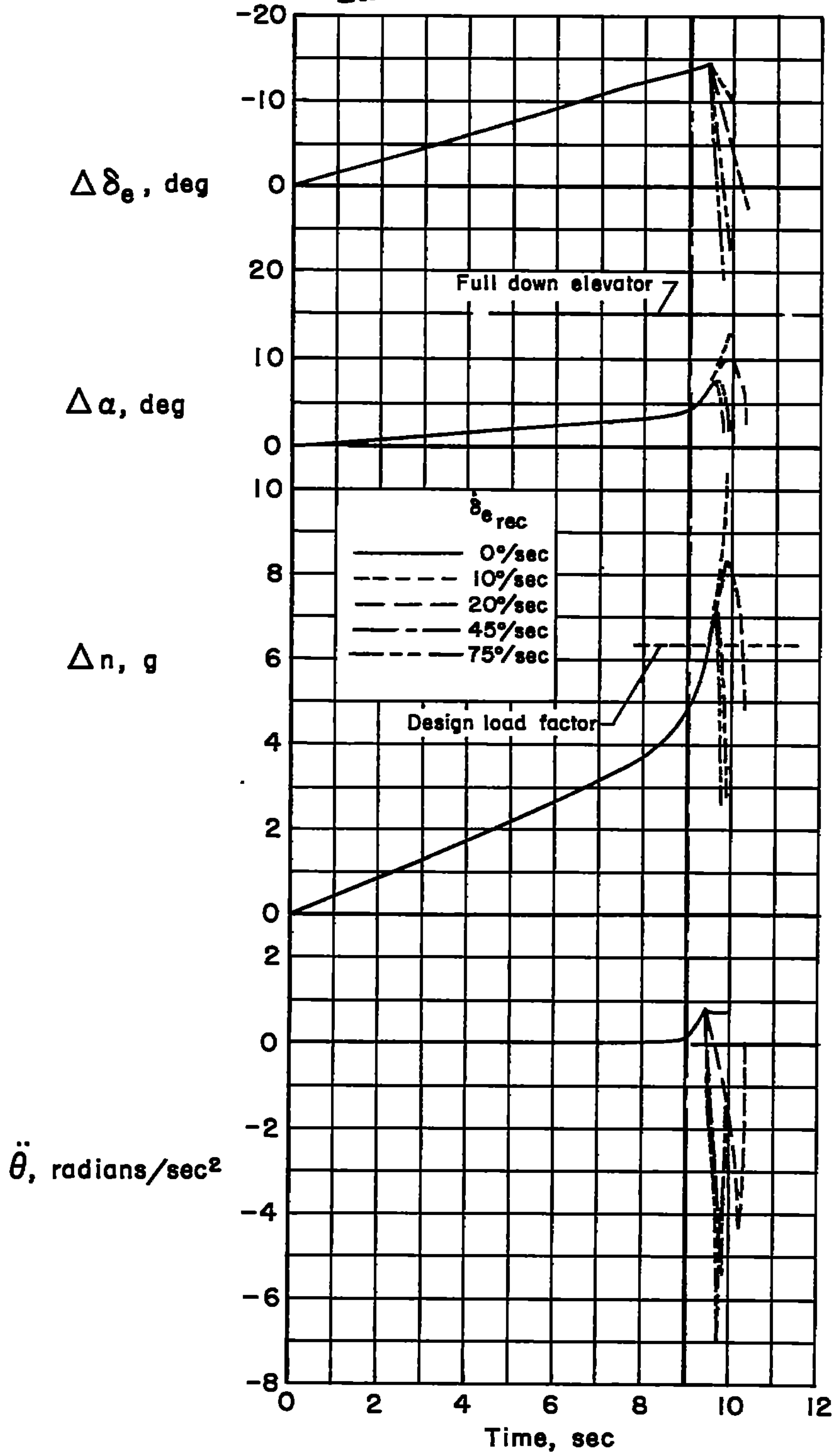
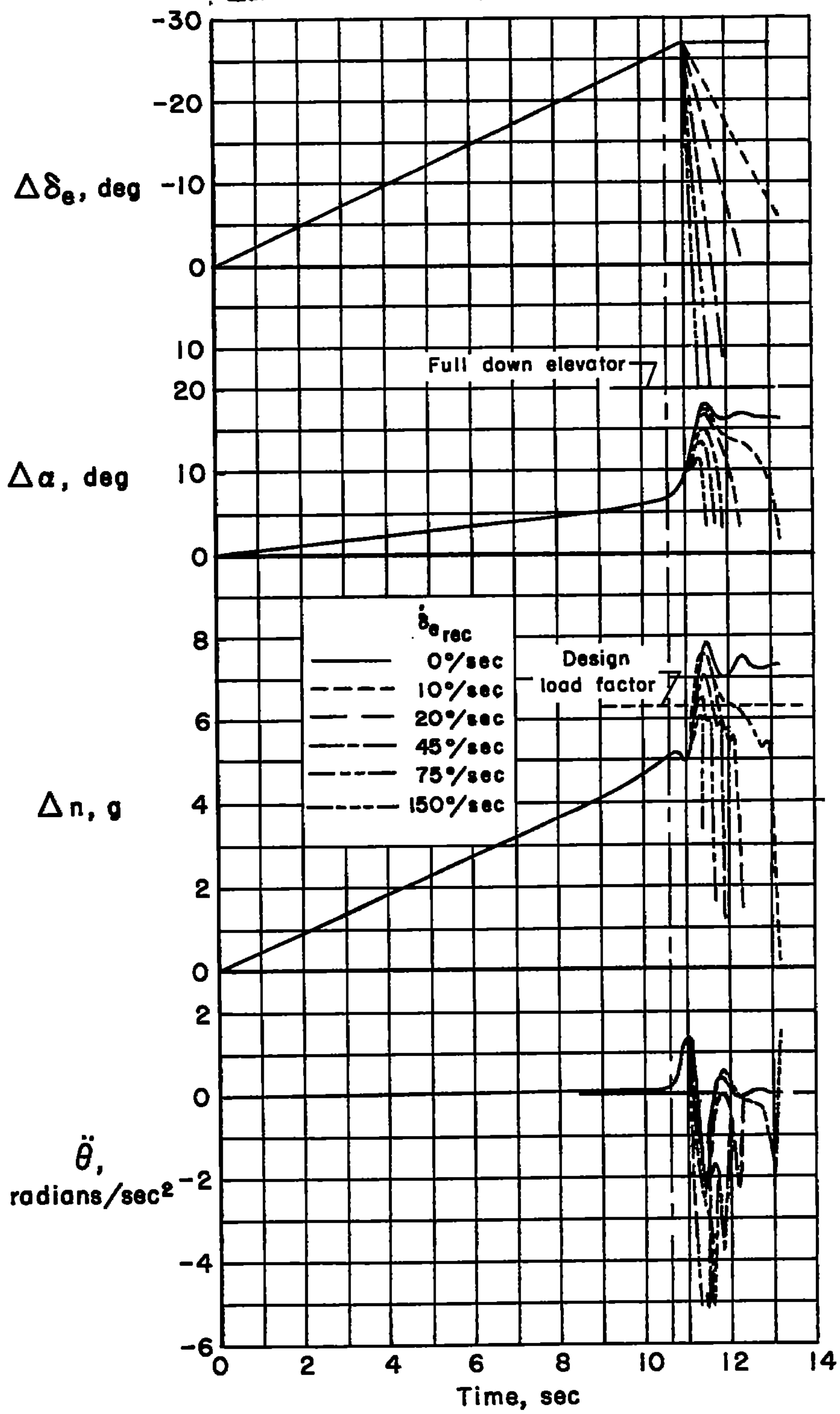


Figure 6.- Computed effect of entry rate on the peak positive pitching acceleration at 35,000 feet; $n_{entry} \approx$ 35- to 55-percent n_{design}.



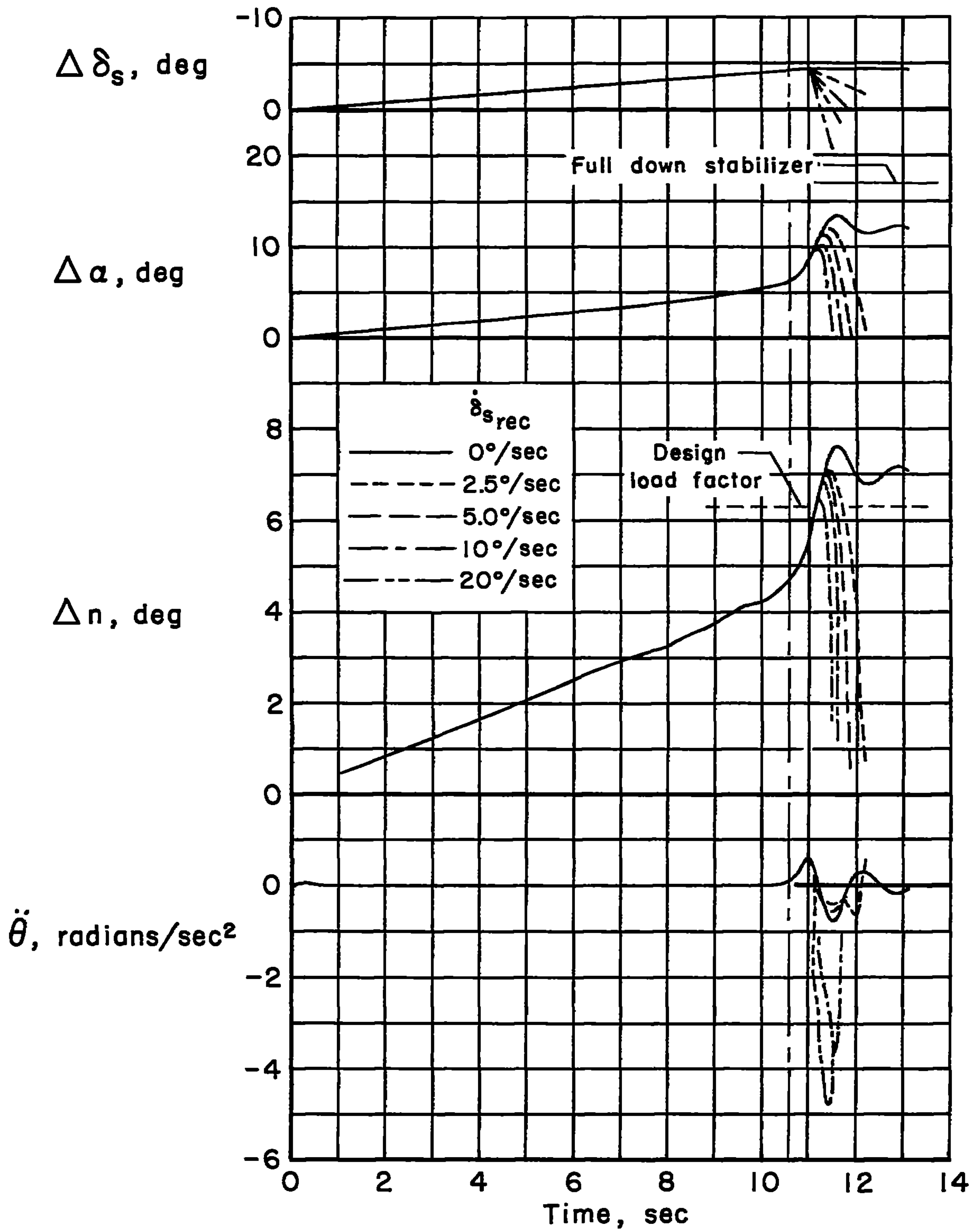
(a) F-86A; Δn_{entry} = 4.9g; h_p = 15,200 feet

Figure 7.- Computed time histories of pitch-up maneuvers at high load factors; $n_{entry} \approx$ 80-percent n_{design}; $\dot{n}_{entry}$ = 0.5g/second.



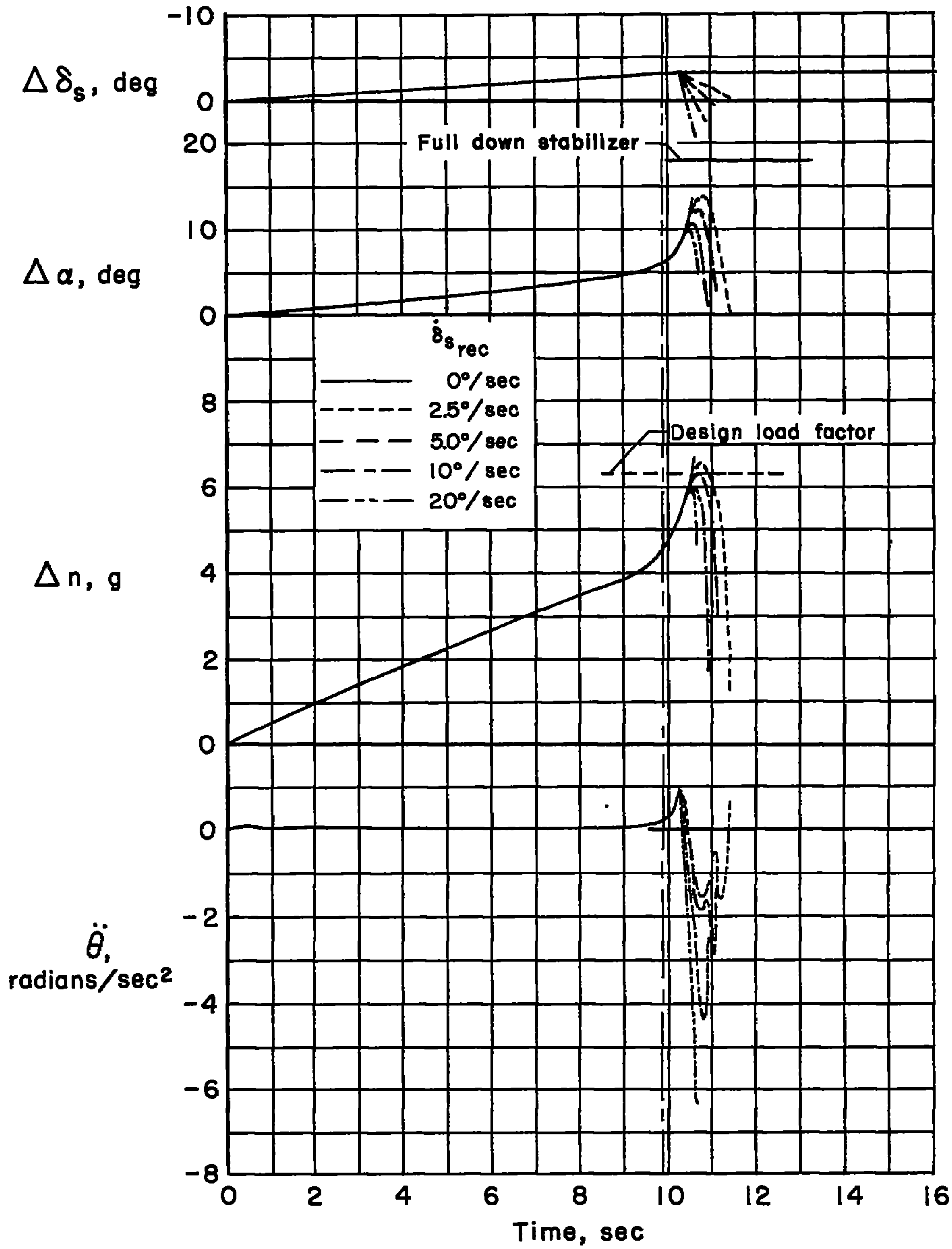
(b) F-84F; Δn_{entry} = 5.0g; h_p = 18,800 feet

Figure 7.- Continued.



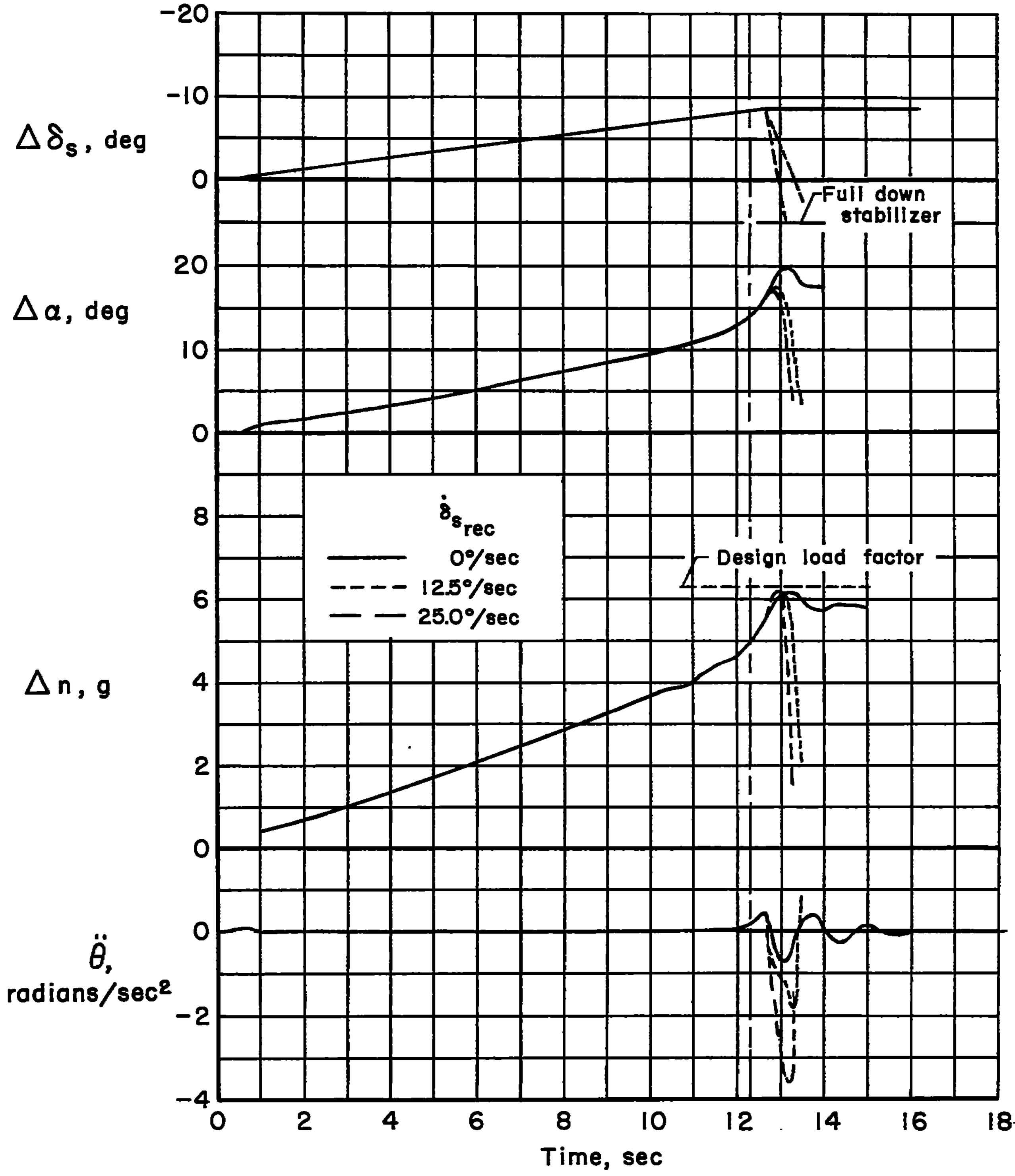
(c) YF-86D; Δn_{entry} = 4.8g; h_p = 17,600 feet

Figure 7.- Continued.



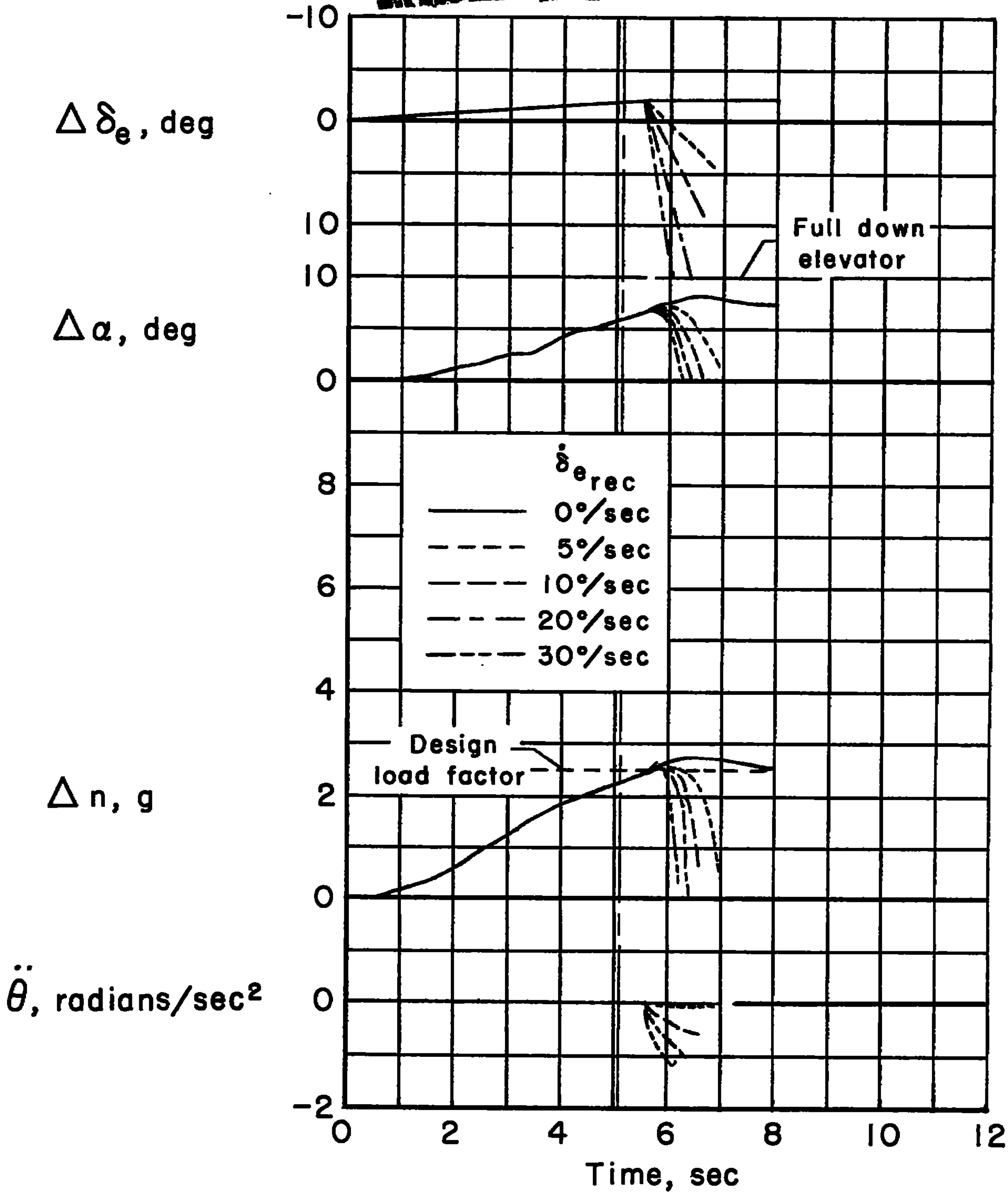
(d) F-86F; Δn_{entry} = 4.7g; h_p = 26,900 feet

Figure 7.- Continued.



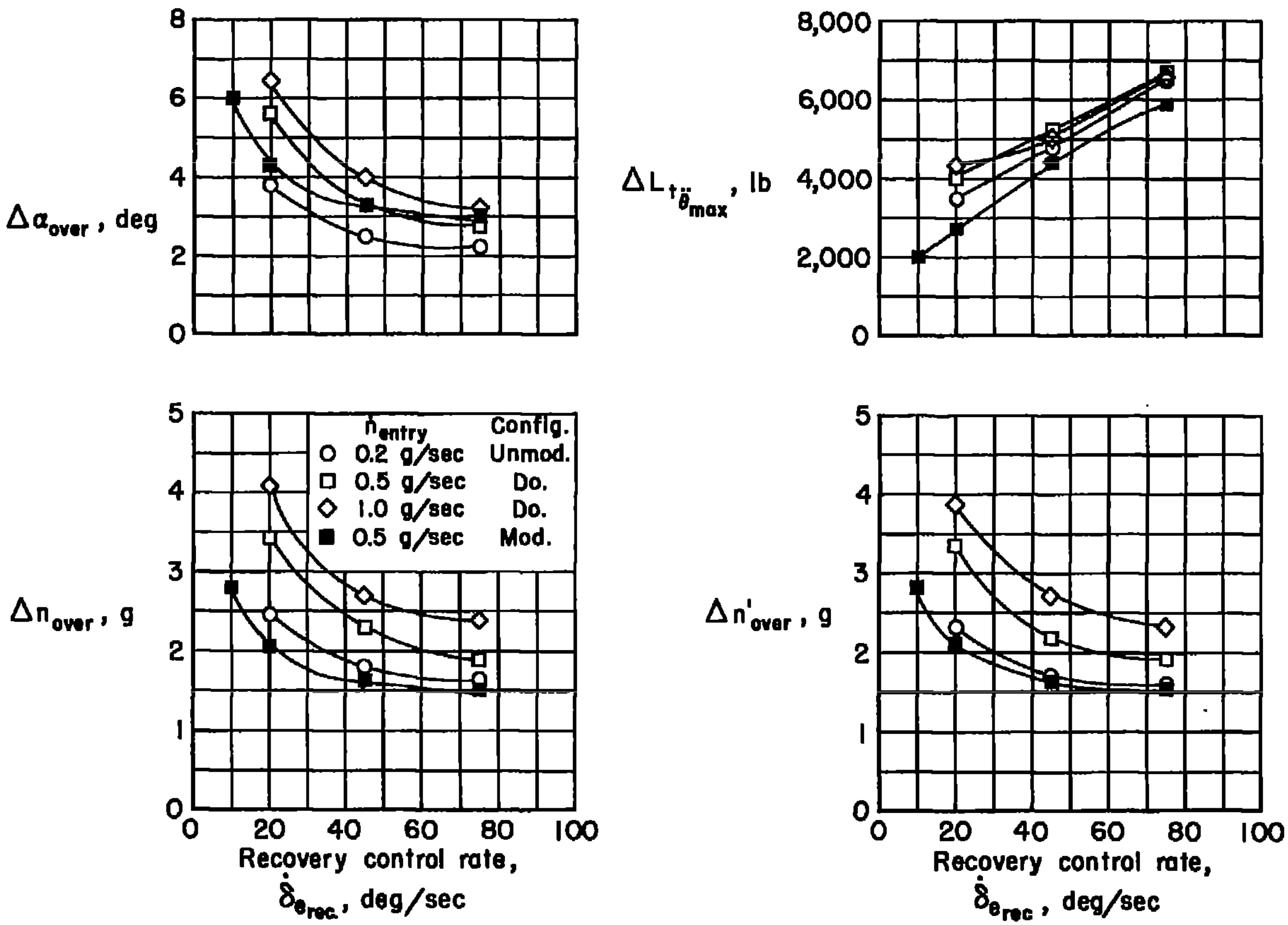
(e) F-100A; Δn_{entry} = 5.0g; h_p = 22,700 feet

Figure 7.- Continued.



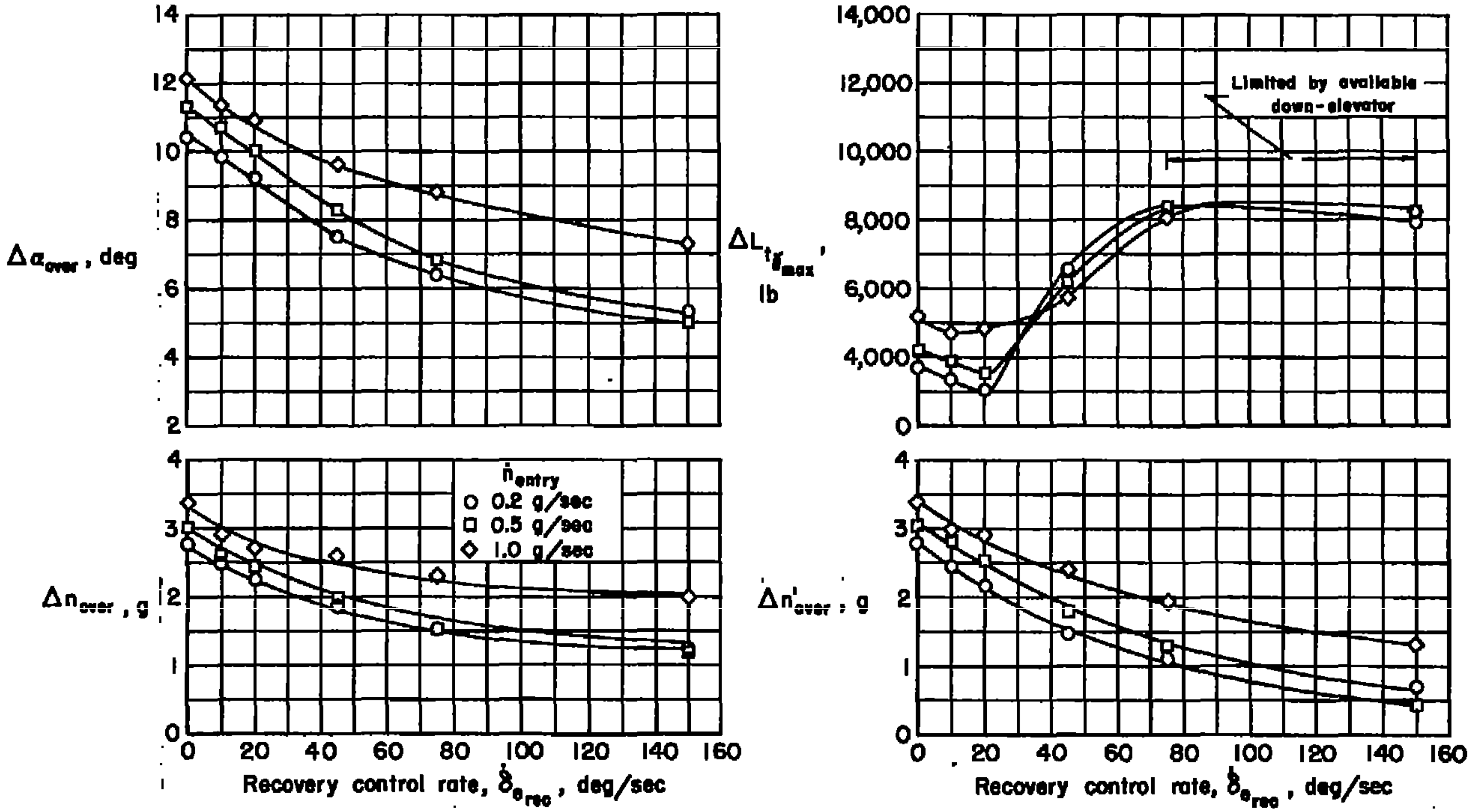
(f) B-47; Δn_{entry} = 2.3g; h_p = 25,800 feet

Figure 7.- Concluded.



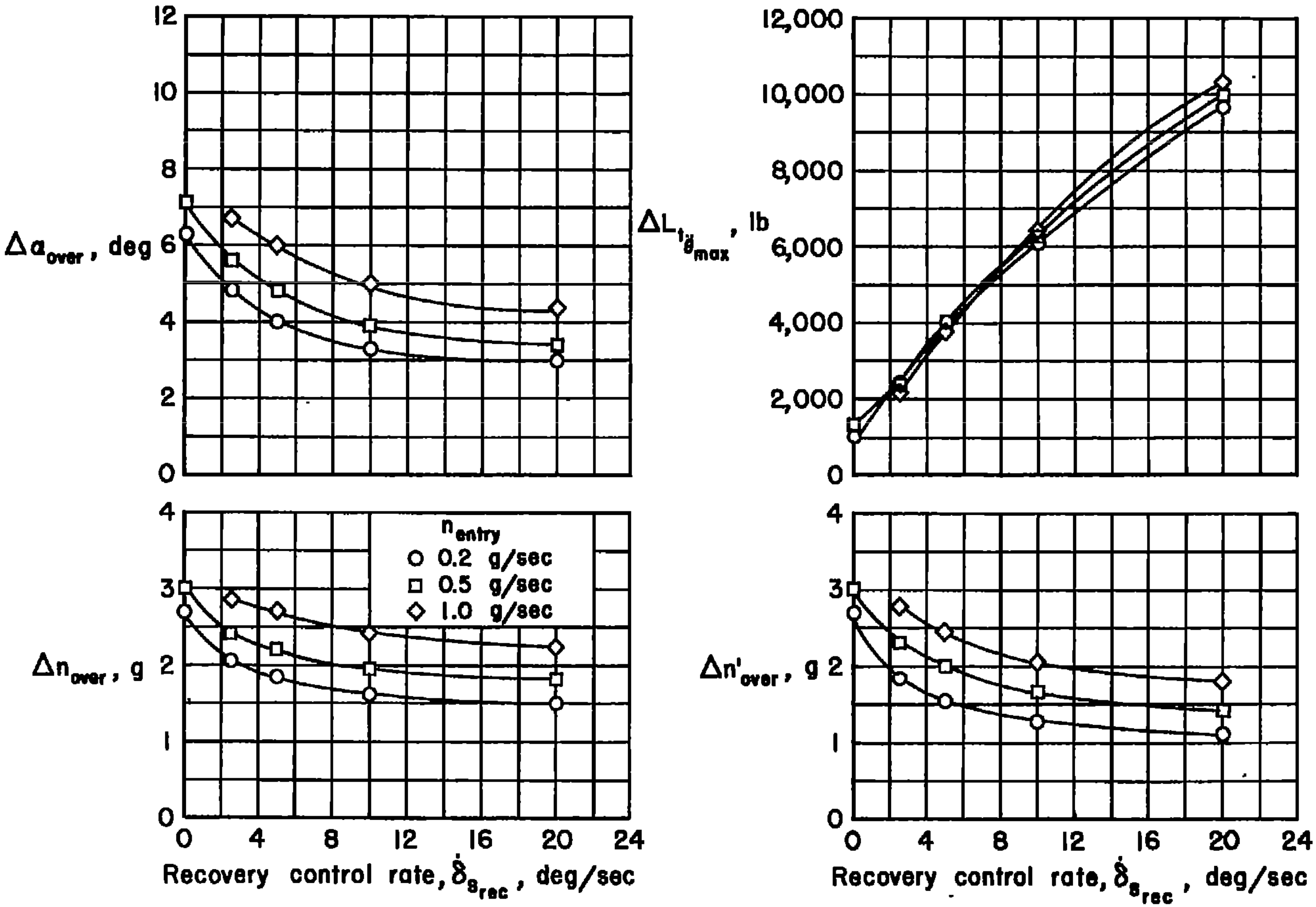
(a) F-86A; Δn_{entry} = 4.9g; h_p = 15,200 feet

Figure 8.- Variation of the computed overshoots in angle-of-attack and load factor and of the maneuvering tail-load increment with recovery-control rate at high load factors for several entry rates; n_{entry} = 80-percent n_{design}.



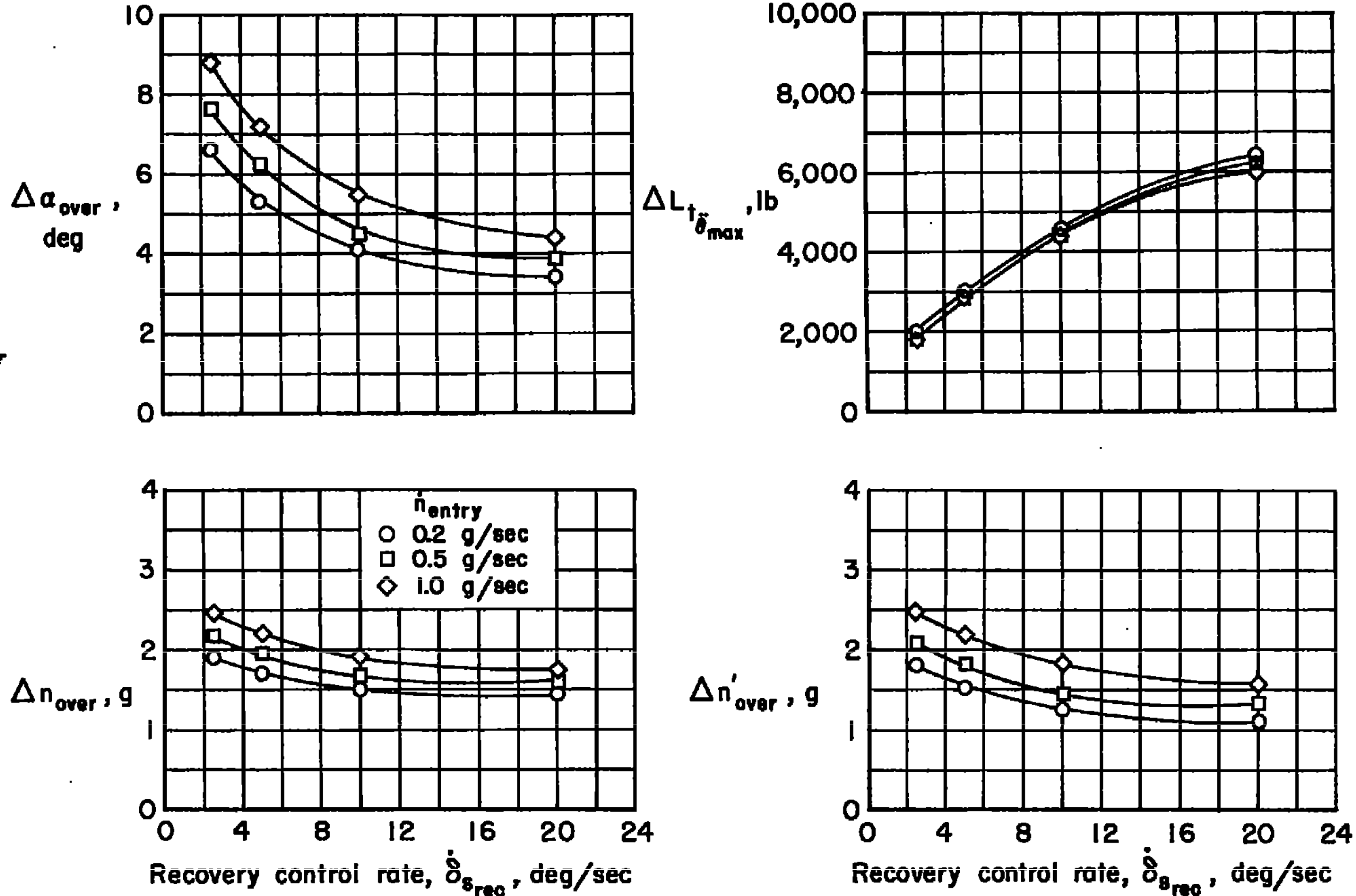
(b) F-84F; Δn_{entry} = 5.0g; h_p = 18,800 feet

Figure 8.- Continued.



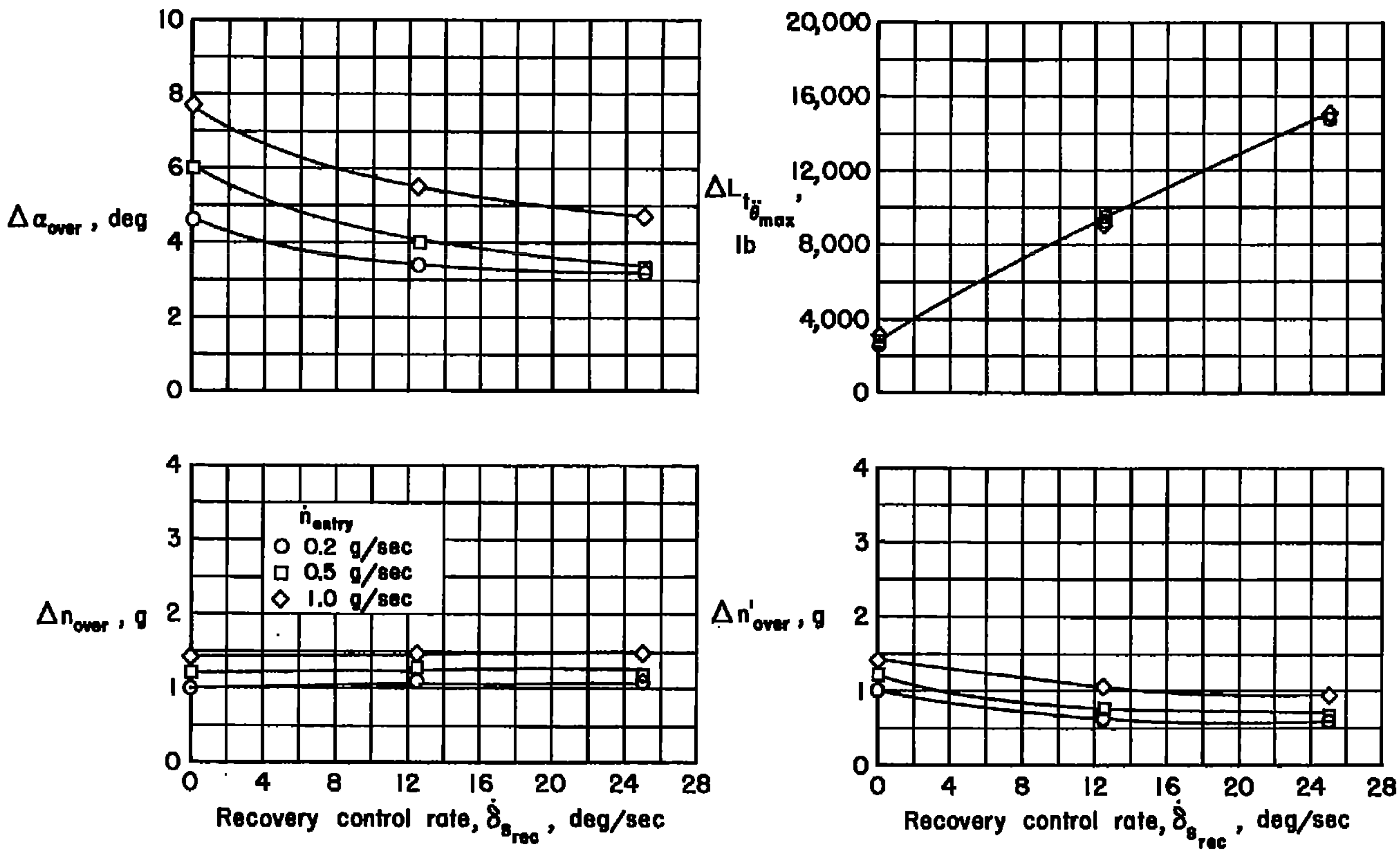
(c) YF-86D; Δn_{entry} = 4.8g; h_p = 17,600 feet

Figure 8.- Continued.



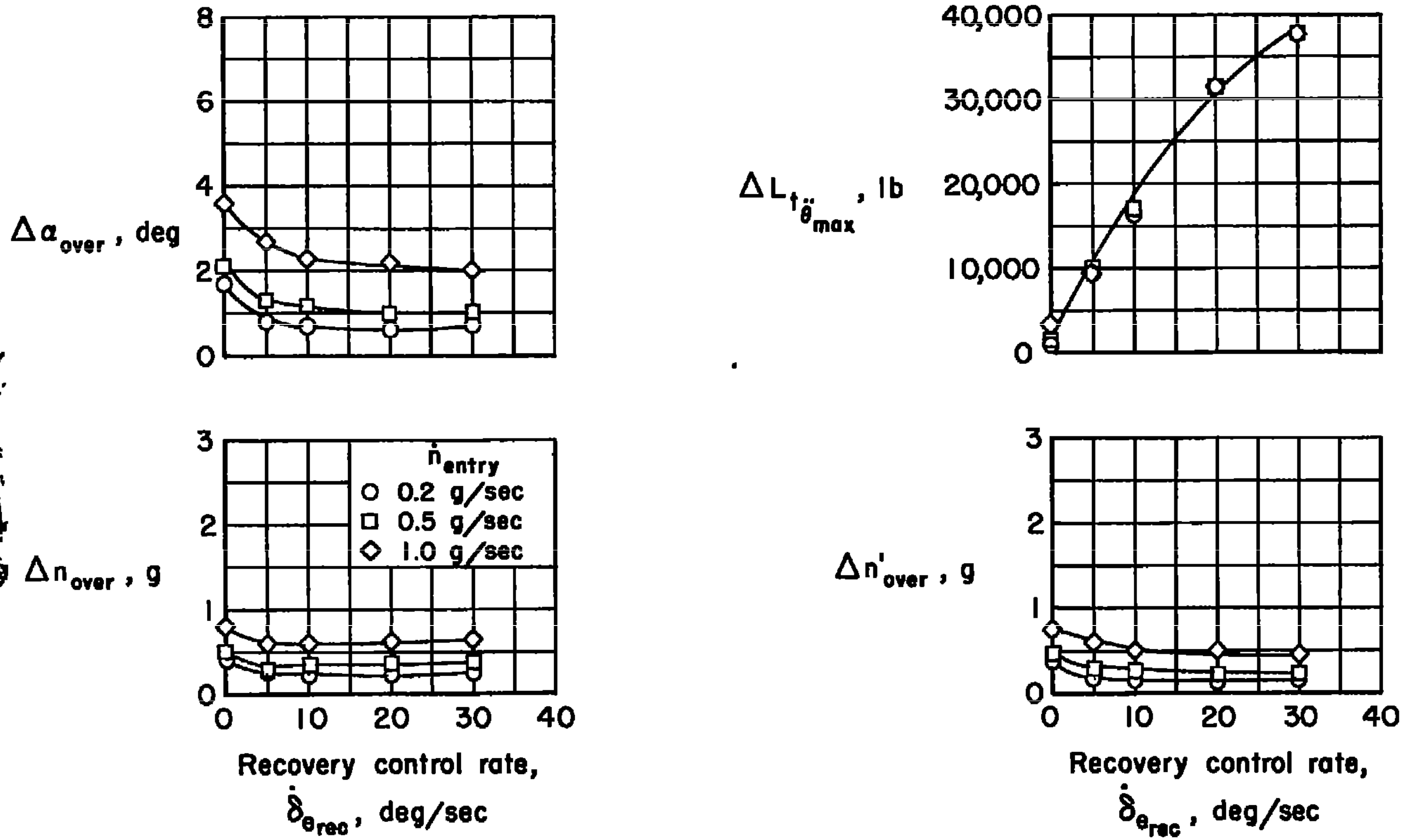
(d) F-86F; Δn_{entry} = 4.7g; h_p = 26,900 feet

Figure 8.- Continued.



(e) F-100A; Δn_{entry} = 5.0g; h_p = 22,700 feet

Figure 8.- Continued.



(f) B-47; Δn_{entry} = 2.3g; h_p = 25,800 feet

Figure 8.- Concluded.

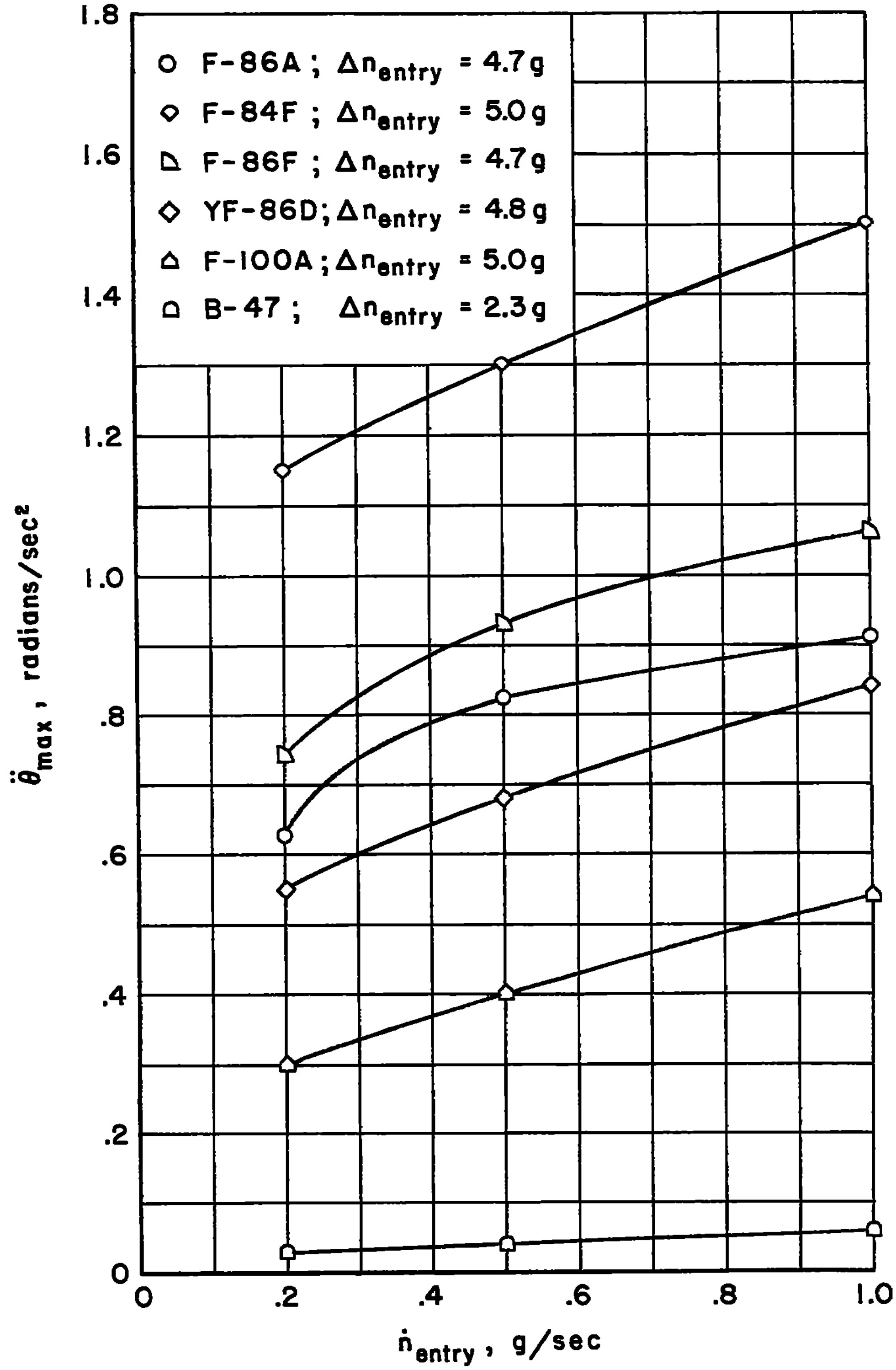
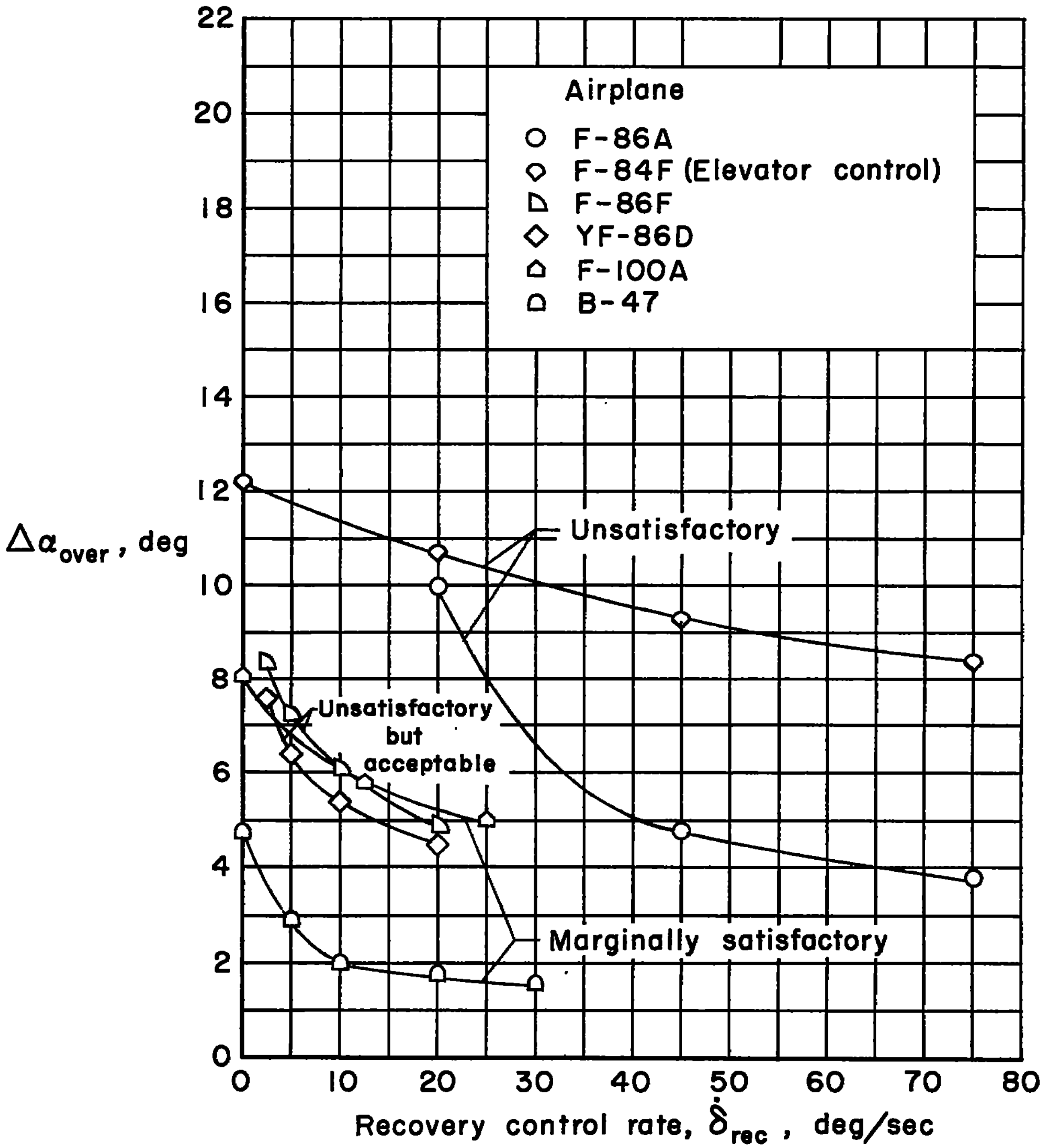
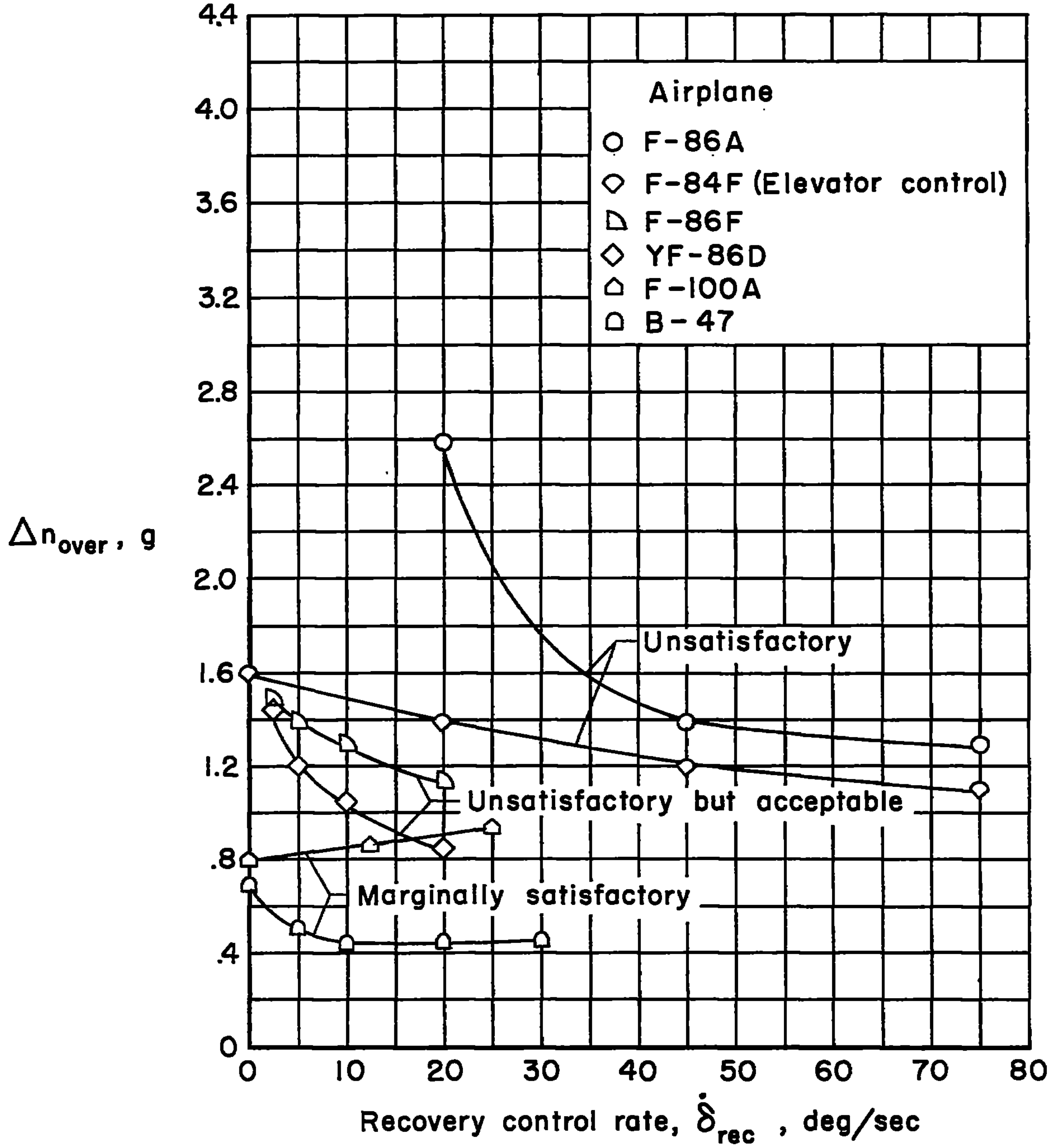


Figure 9.- Computed effect of entry rate on the peak positive pitching acceleration at high load factors; $n_{entry} \approx$ 80-percent n_{design}.



(a) Angle-of-attack overshoot.

Figure 10.- Correlation of the computed overshoots with over-all pilot opinion of the pitch-up characteristics for the six airplanes studied; $M \approx 0.90$; $h_p \approx 35{,}000$ feet; $\dot{n}_{entry} = 0.5g$/second.



(b) Airplane load-factor overshoot.

Figure 10.- Concluded.

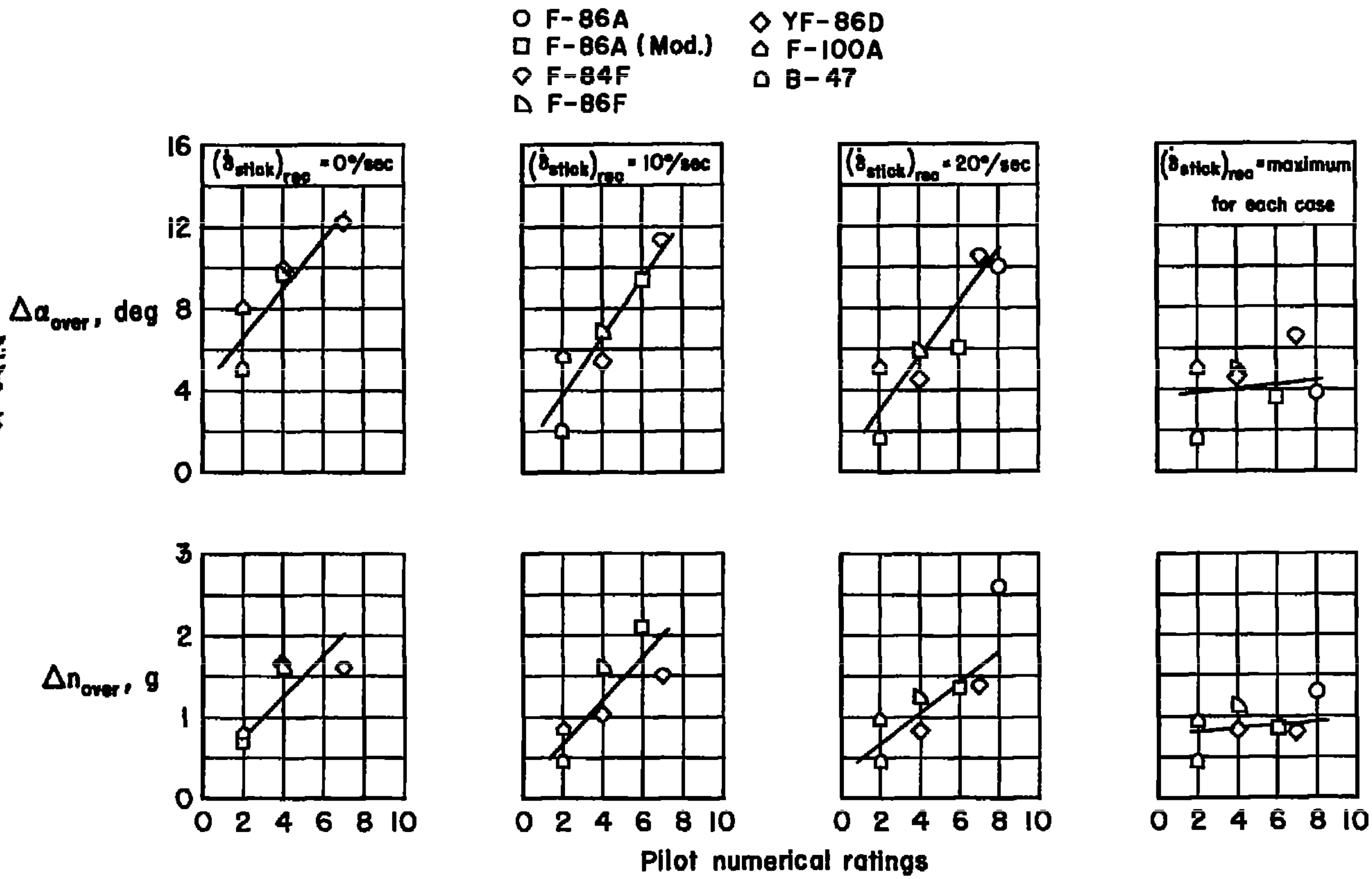


Figure 11.- Correlation of the computed overshoots in angle of attack and load factor with the pilot's over-all pitch-up ratings for several airplanes; h_p = 35,000 feet; $\dot{n}_{entry} \approx 0.5g$/second.

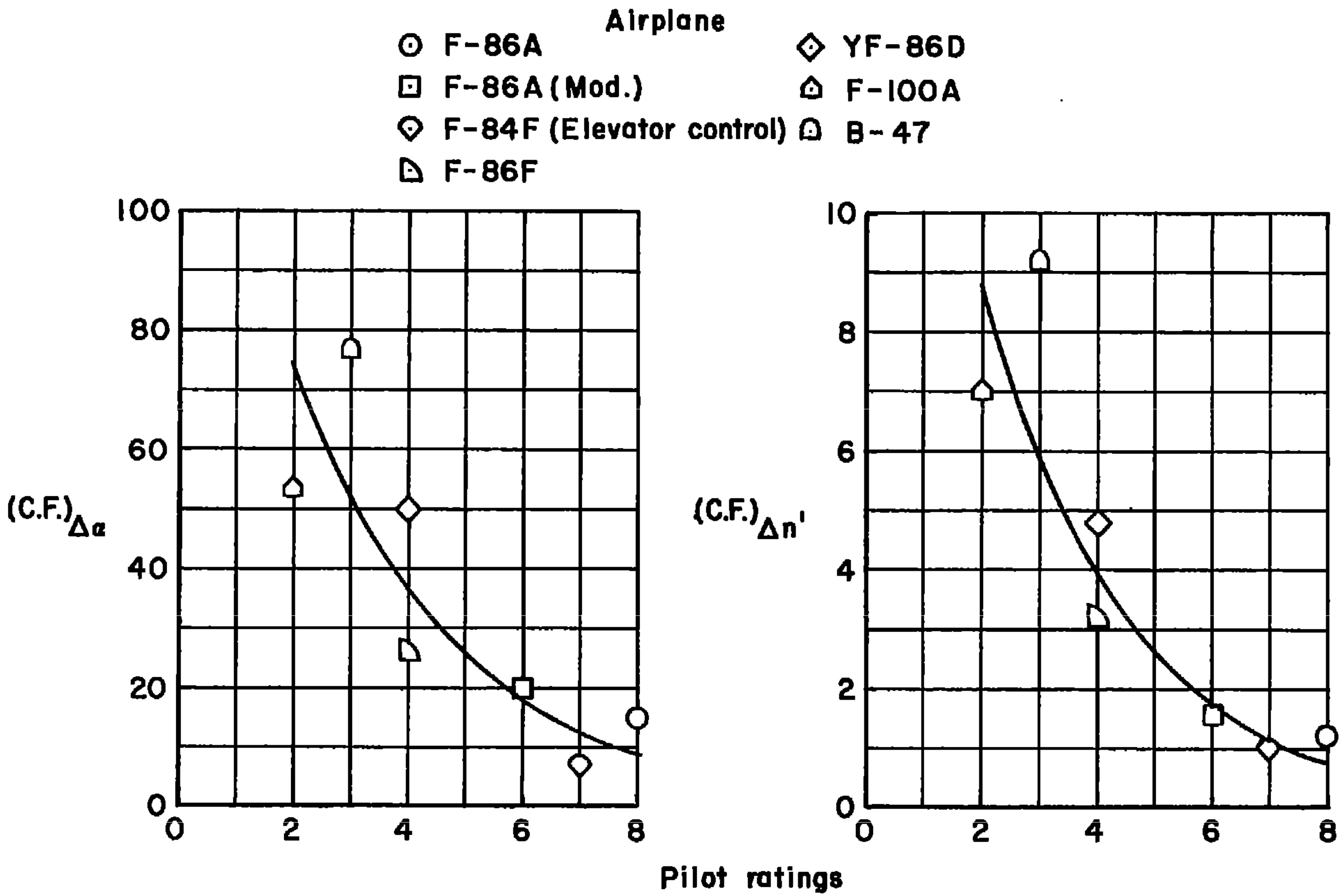


Figure 12.- Correlation of the computed attitude and load-factor controllability factors with the pilot's over-all rating of the pitch-up characteristics for several airplanes; $h_p = 35{,}000$ feet; $\dot{n}_{entry} \approx 0.5g$/second.

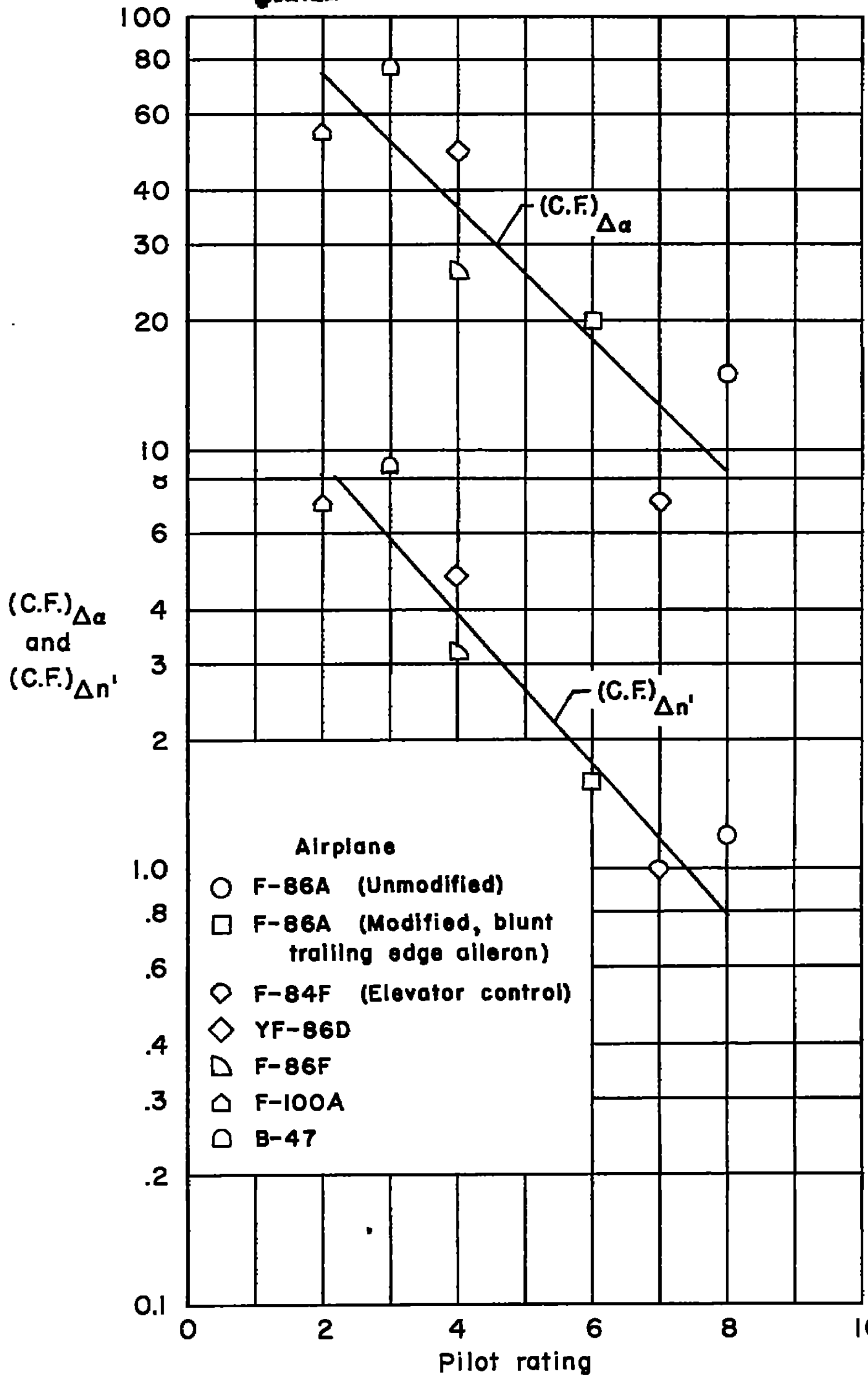
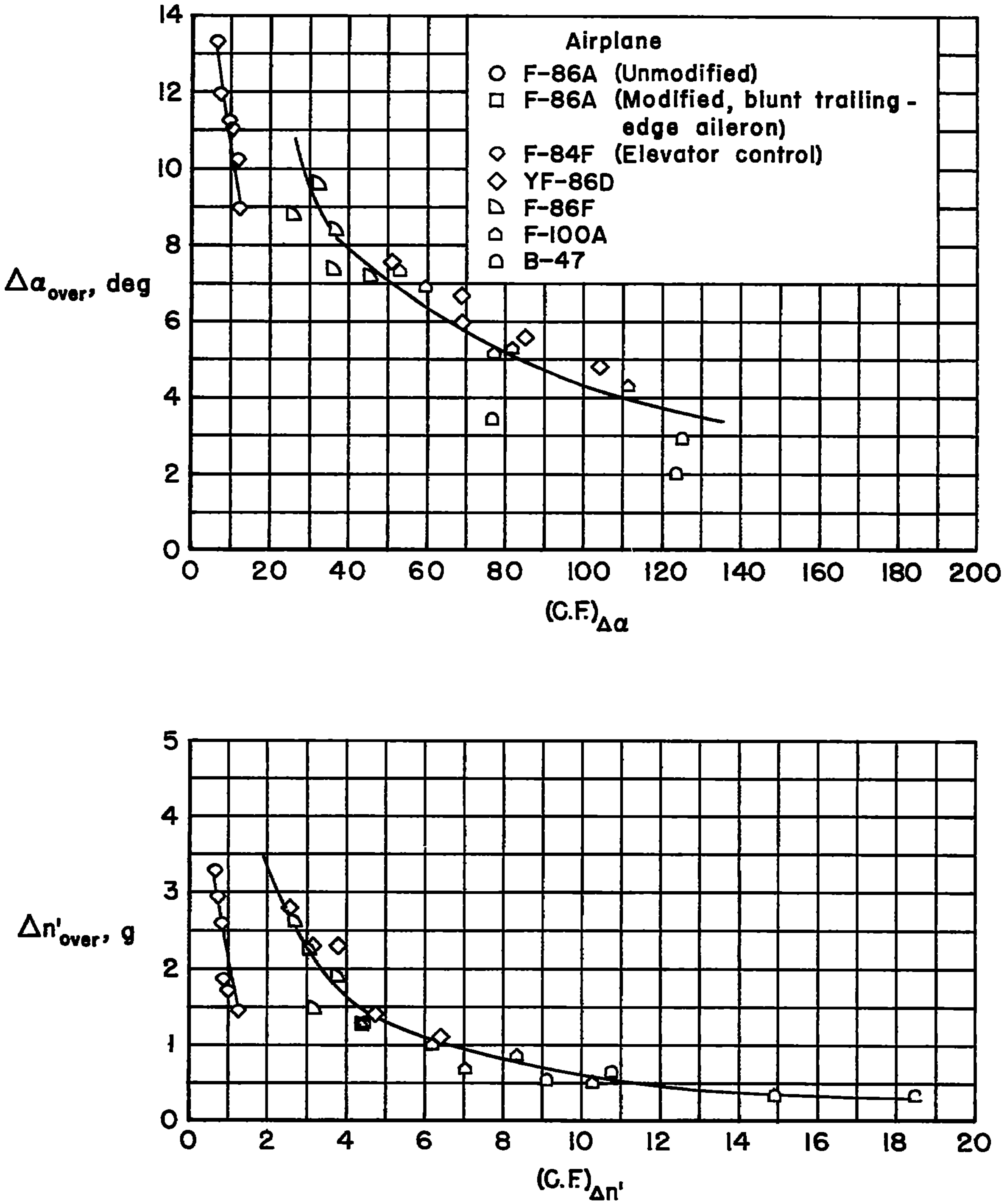
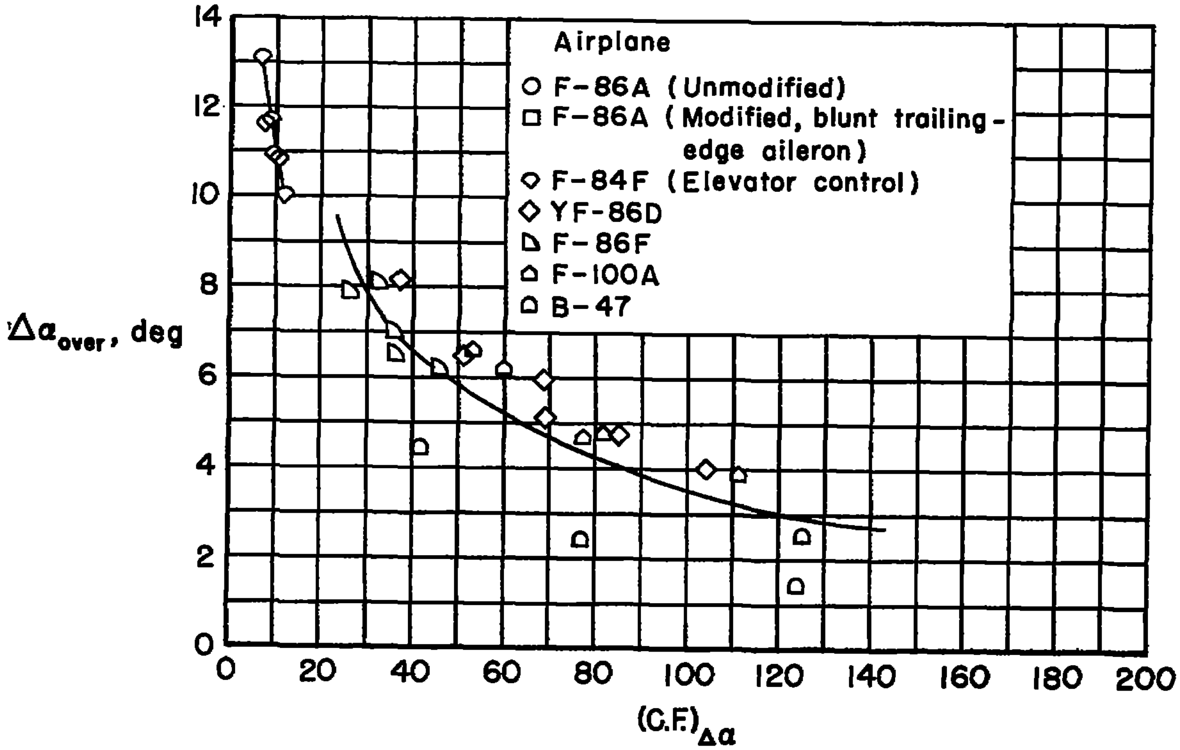


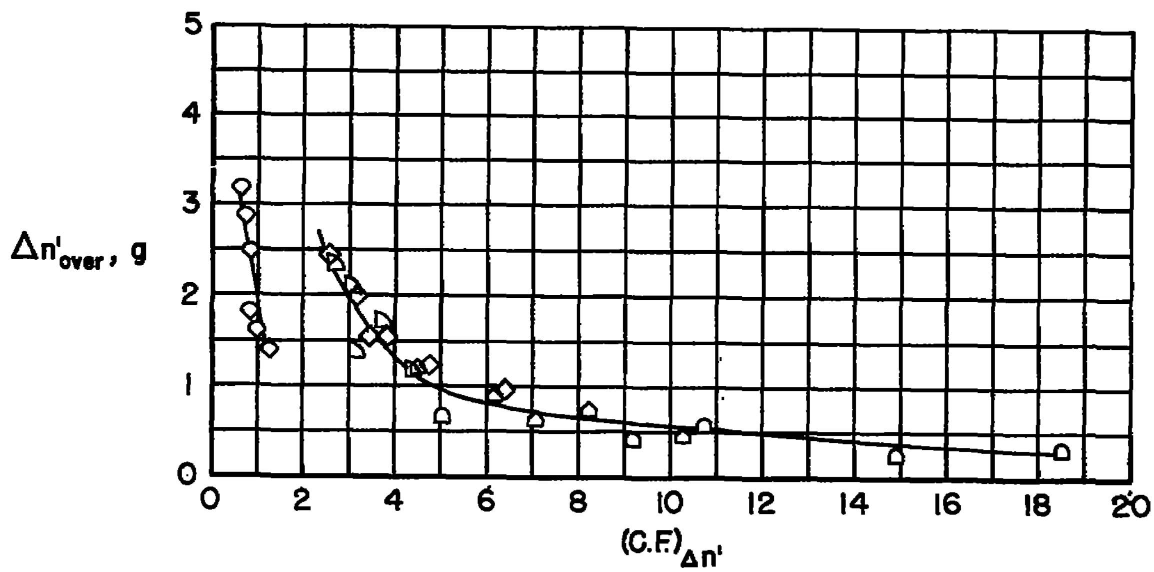
Figure 13.- Correlation of log of the computed controllability factors with pilot's over-all flight-test ratings of pitch-up for several airplanes; h_p = 35,000 feet; $\dot{n}_{entry} \approx 0.5g$/second.



(a) $(\dot{\delta}_{stick})_{rec}$ = 2.5°/second

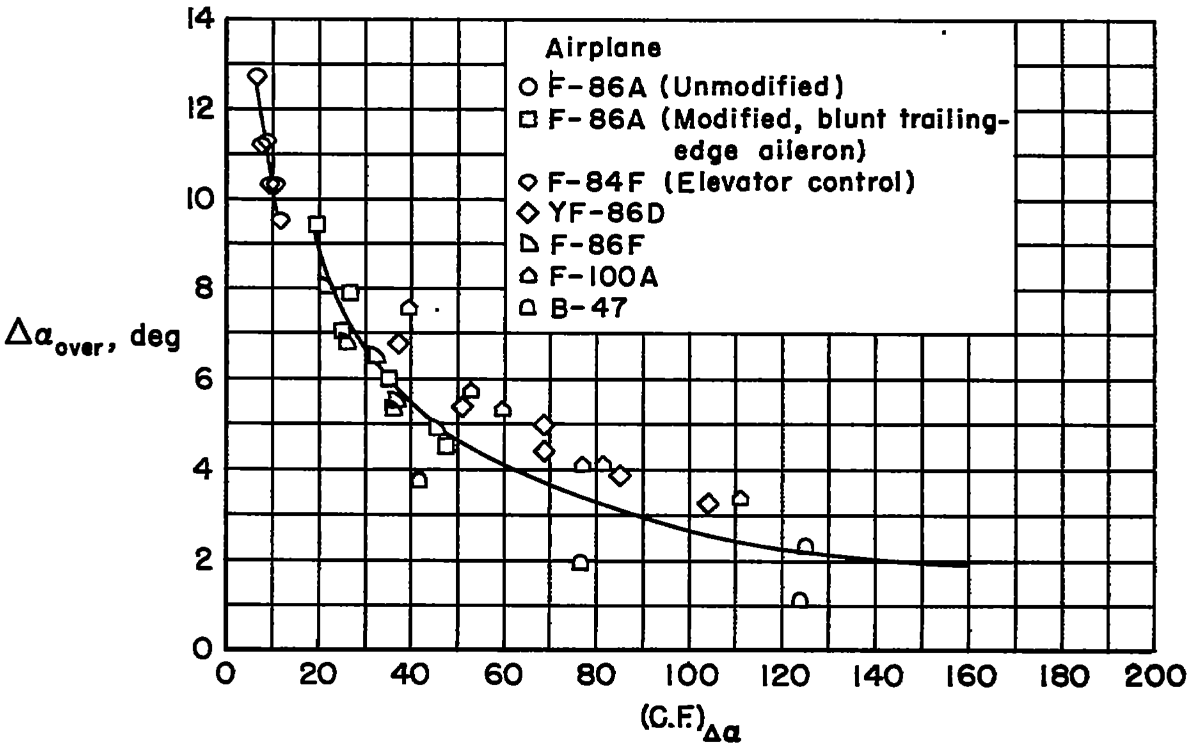
Figure 14.- Variation of the overshoot in angle of attack and in load factor due to angle of attack with the controllability factors $(C.F.)_{\Delta\alpha}$ and $(C.F.)_{\Delta n'}$, respectively, for several stick-recovery rates.

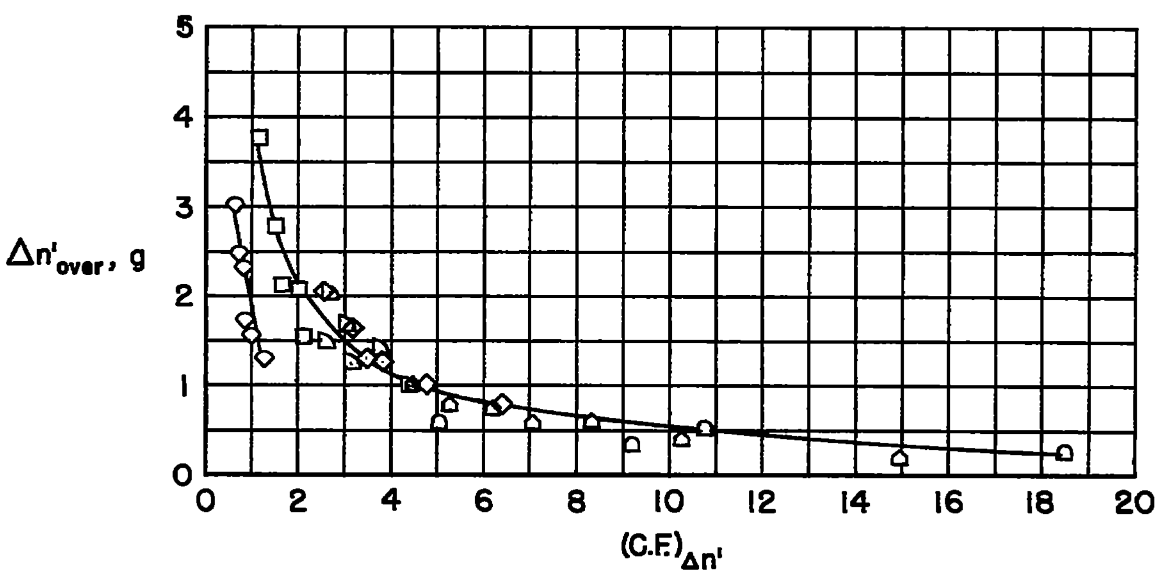




(b) $(\dot{\delta}_{stick})_{rec} = 5^{\circ}$/second

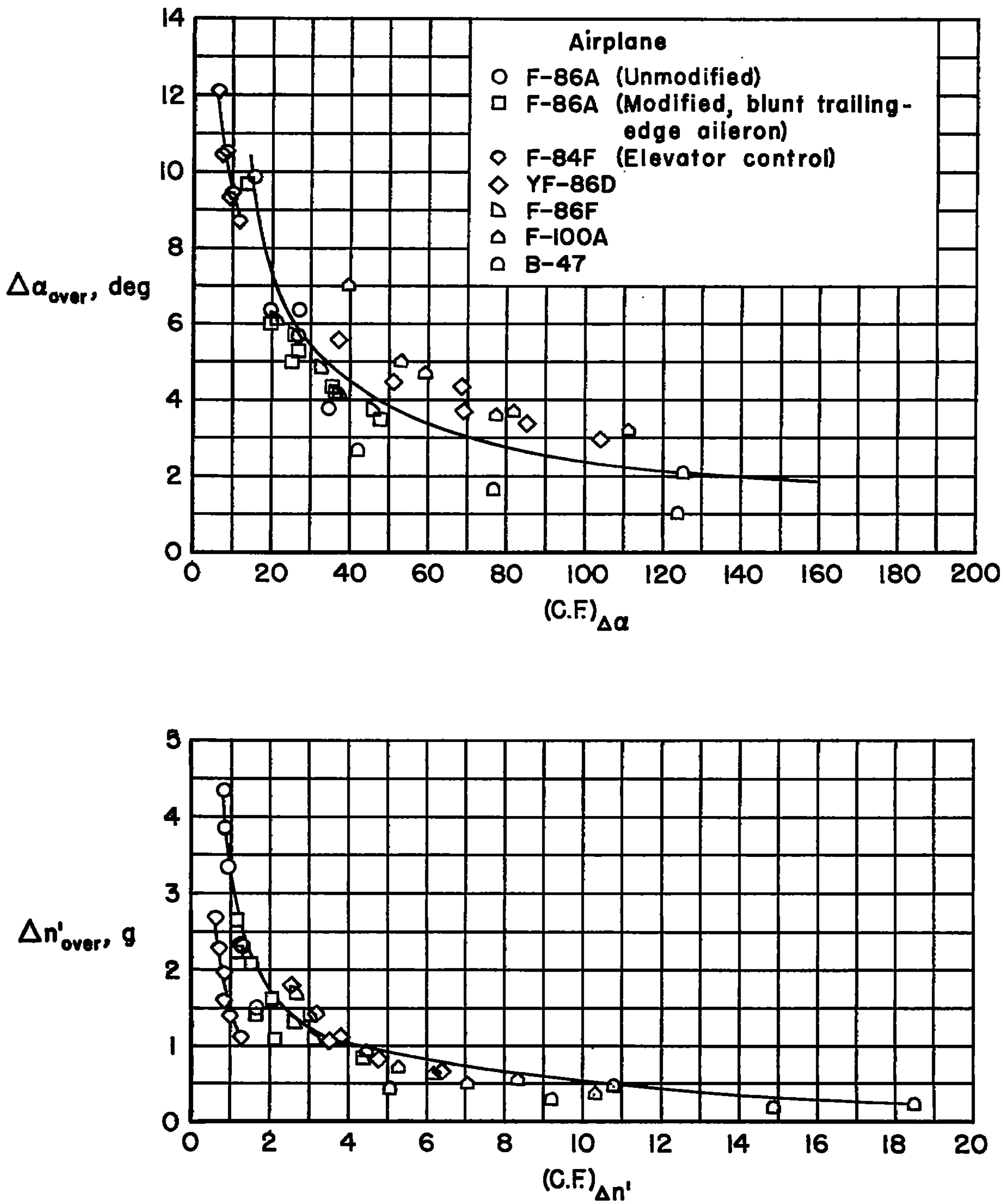
Figure 14.- Continued.





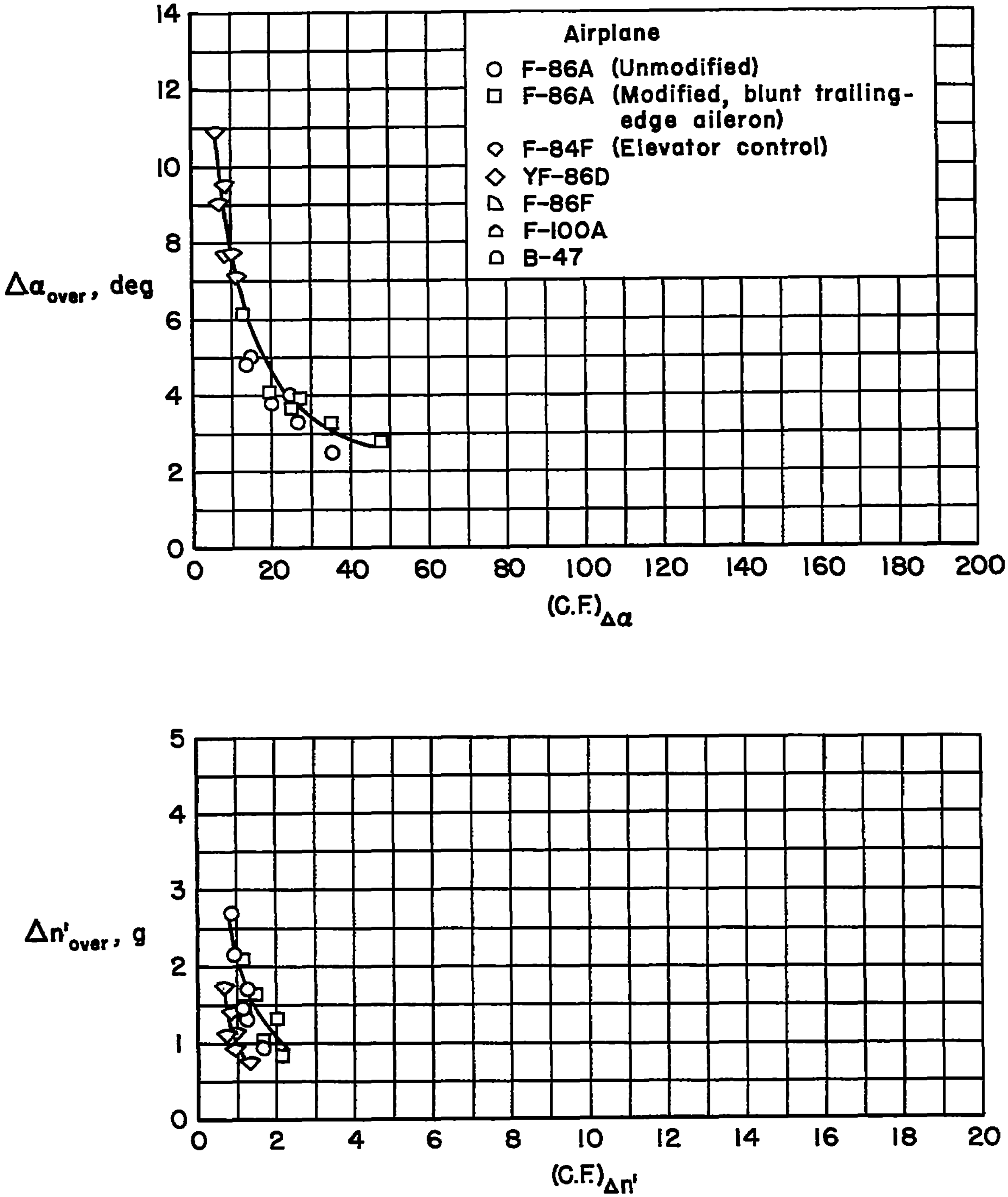
(c) $(\dot{\delta}_{stick})_{rec} = 10^{\circ}$/second

Figure 14.- Continued.



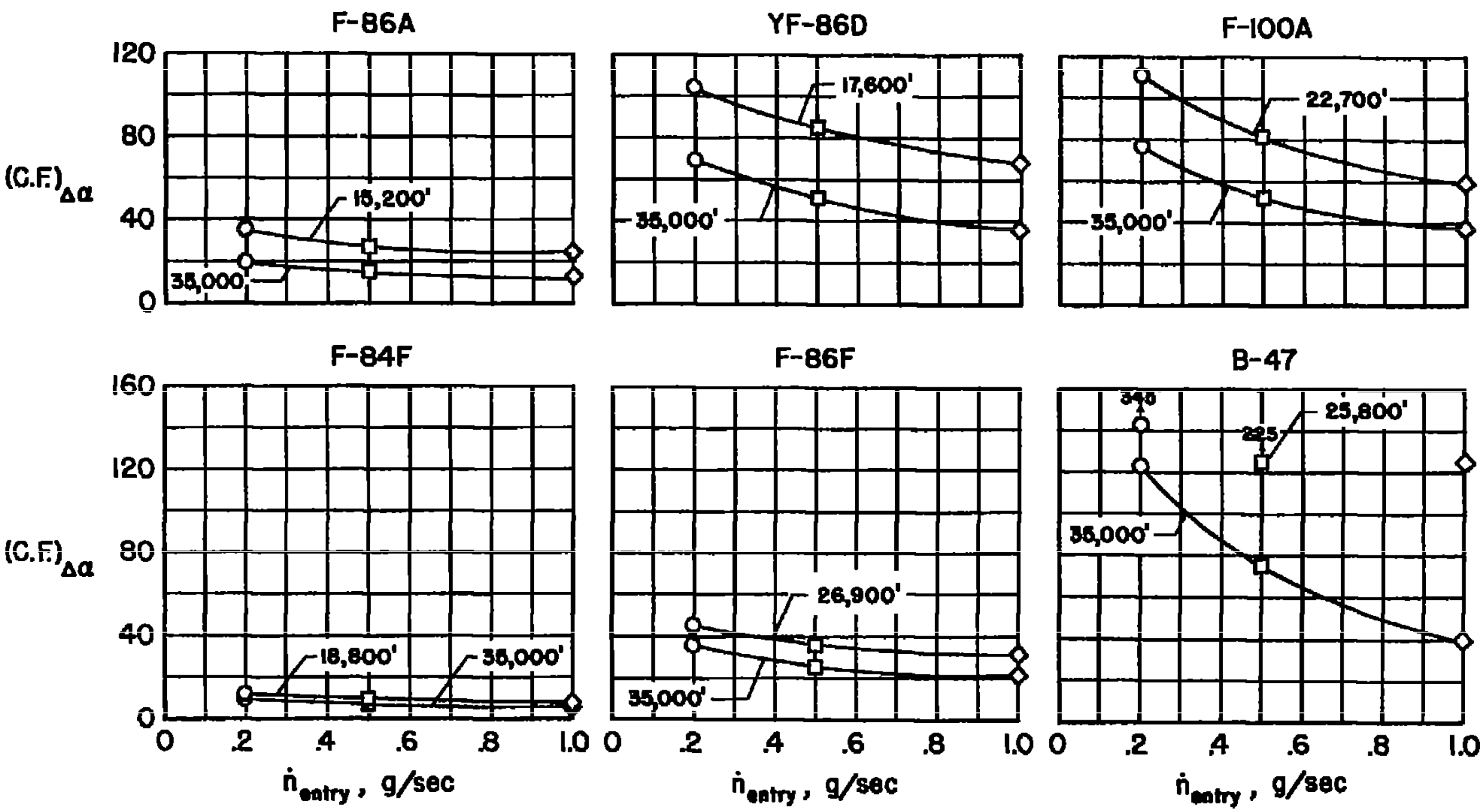
(d) $(\dot{\delta}_{stick})_{rec} = 20^{\circ}$/second

(Figure 14.- Continued.



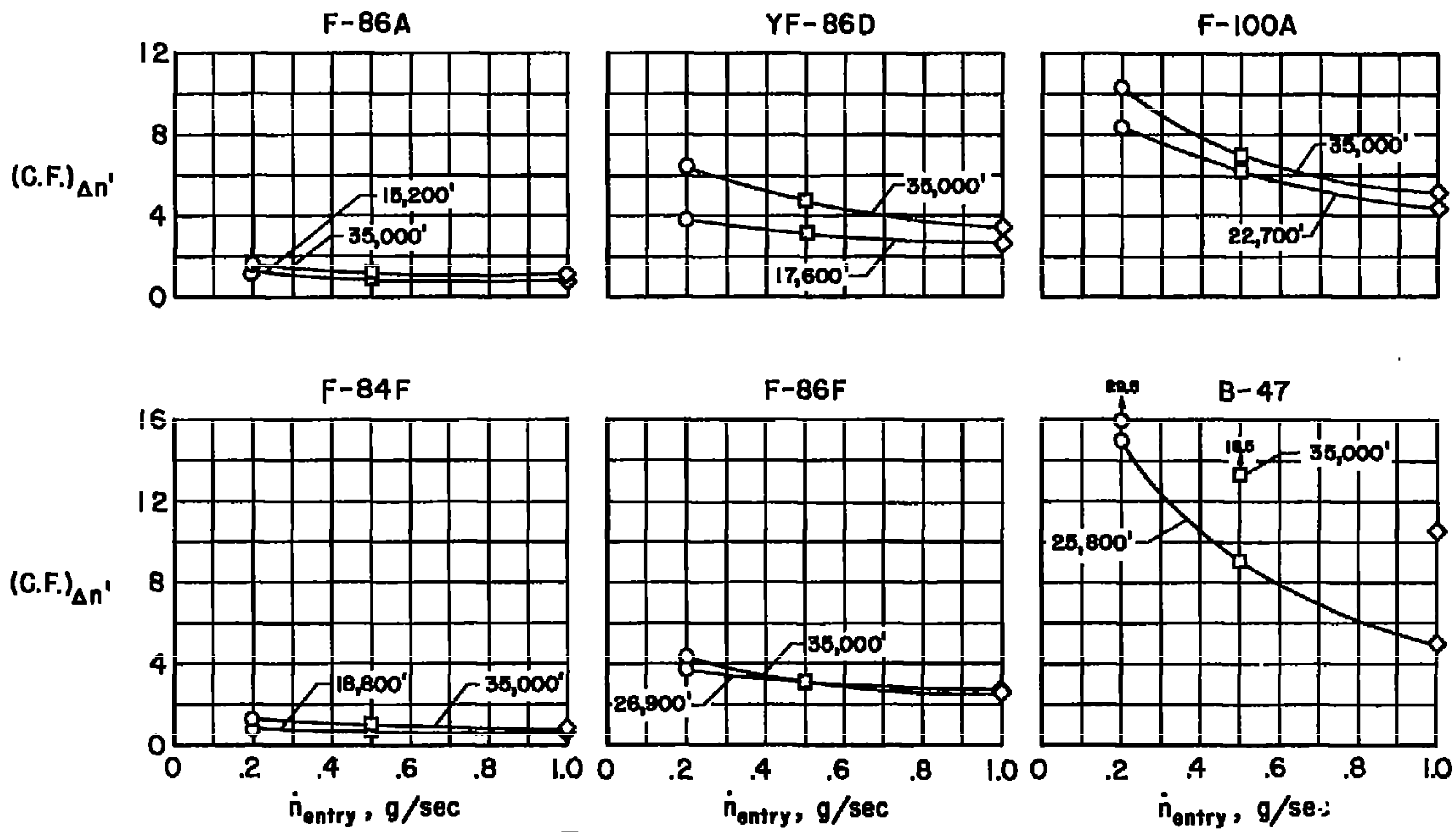
(e) $(\dot{\delta}_{stick})_{rec} = 45^{\circ}$/second

Figure 14.- Concluded.



(a) Effect on attitude controllability factor.

Figure 15.- Effect of entry rate and altitude on the computed controllability factors.



(b) Effect on load-factor controllability factor.

Figure 15.- Concluded.

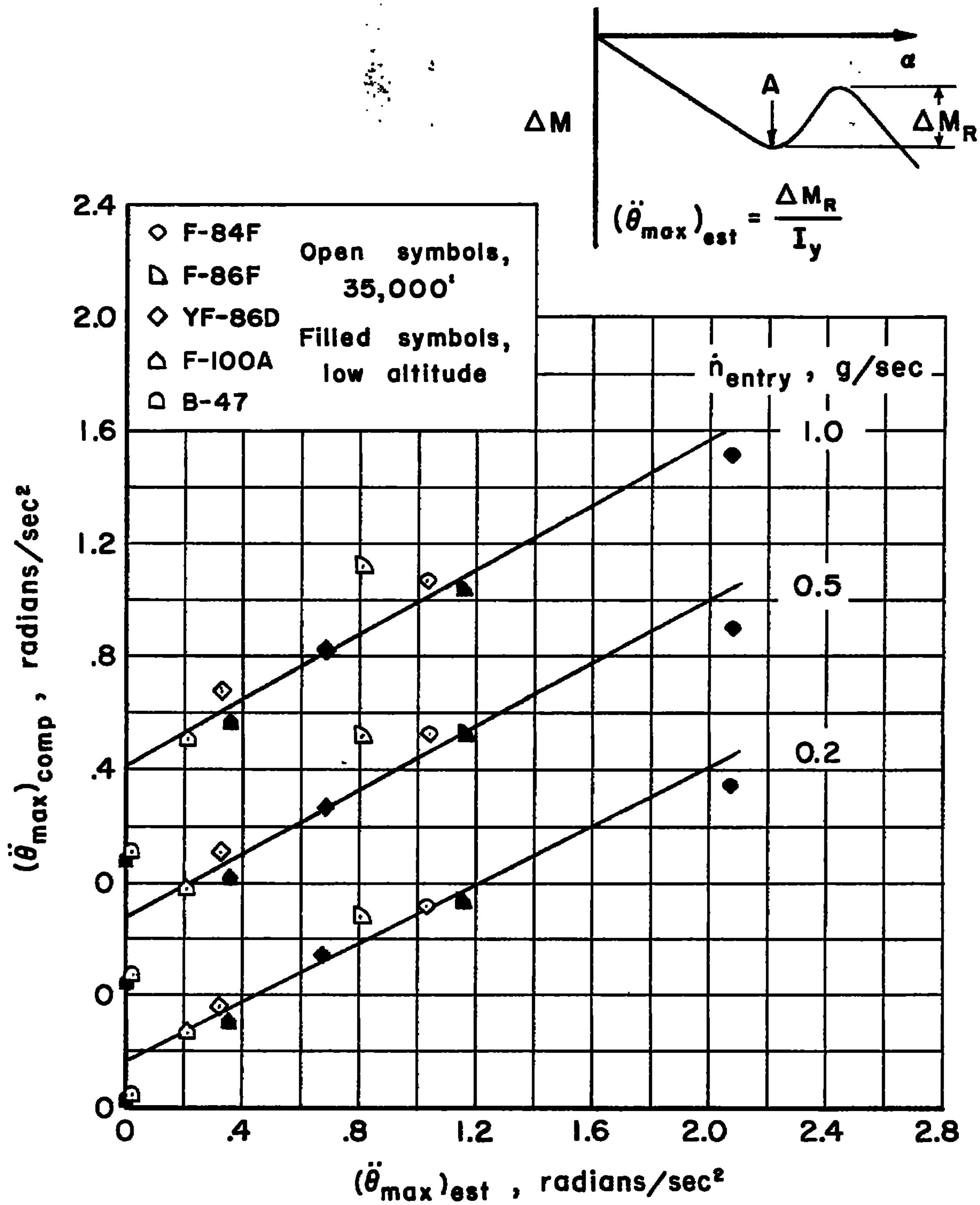


Figure 16.- Variation of computed peak positive pitching acceleration in pitch-up maneuvers with values estimated directly from the variation of pitching moment with angle of attack of several airplanes.